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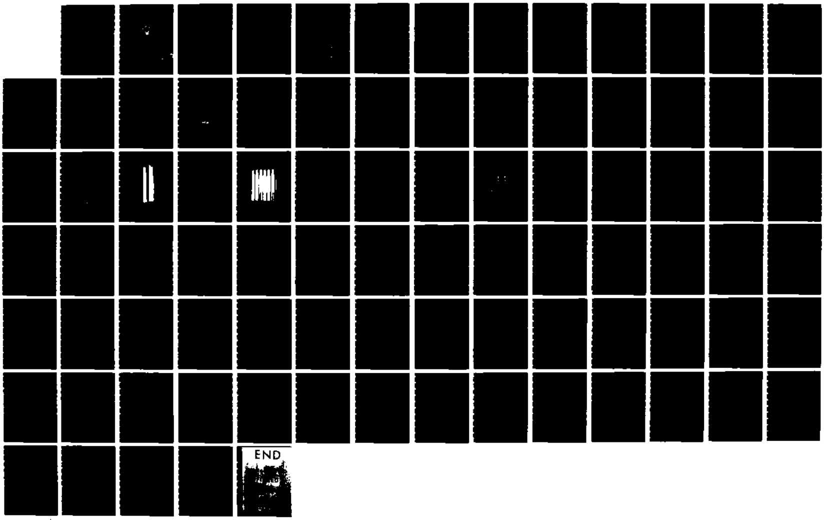

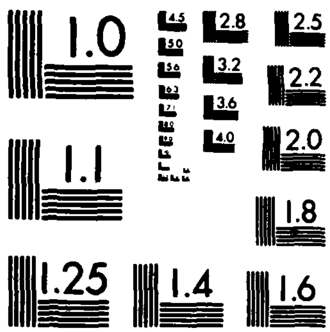

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NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

FILMWISE CONDENSATION OF STEAM ON
EXTERNALLY-FINNED HORIZONTAL TUBES

by

William M. Poole

December 1983

Thesis Advisor: P. J. Marto

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Condensation data taken for the smooth tube were compared with data in the literature to check the reliability of the apparatus and the data-reduction procedures. The data for the finned tubes showed an optimum pitch of 2.5 mm.

Filmwise Condensation of Steam on Externally-finned Horizontal Tubes

by

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Lieutenant, United States Navy
B.S., Marine Engineering
U.S. Naval Academy, 1978

Submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN MECHANICAL ENGINEERING

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ABSTRACT

The film-condensation characteristics of a smooth tube and six externally-finned tubes having fins 1 mm high and 1 mm thick, and pitches of 1.5, 2.0, 2.5, 3.0, 5.0, and 10.0 mm, were experimentally tested.

A smooth copper tube with an active length of 133.5 mm, an outside diameter of 19.05 mm, and an inside diameter of 12.7 mm was first tested to correlate the inside heat-transfer coefficient using the Sieder-Tate equation. The leading coefficient for this equation was found to be 0.034 + or - $\pm$ 0.001, and was used to derive the external condensing coefficient for all of the tubes by subtracting the inside and wall resistances from the measured overall resistance. The condensing coefficient was measured, both at atmospheric pressure and vacuum (84 mm Hg), with the heat flux as a variable.

Condensation data taken for the smooth tube were compared with data in the literature to check the reliability of the apparatus and the data-reduction procedures. The data for the finned tubes showed an optimum pitch of 2.5 mm.

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NOMENCLATURE

c_p	Specific heat, kJ/kg-K
D_i	Inner diameter, m
D_o	Outer diameter, m
F	Parameter, $g d \mu h_{fg}/u^2 k \overline{\Delta T}$
g	Acceleration due to gravity, m/s^2
Gr_A	Grashof number of air, $g\beta(T_w - T_\infty) L^3/\nu^2$
h	Heat-transfer coefficient, W/m^2-K
h_{fg}	Latent heat of vaporization, kJ/kg
k	Thermal conductivity, W/m-K
k_A	Thermal conductivity of air, W/m-K
k_G	Thermal conductivity of glass, W/m-K
k_L	Thermal conductivity of liquid, W/m-K
L	Length, m
L_B	Length of the boiler, m
Nu	Nusselt number, hd_o/k
p	Pressure, MPa
Pr	Prandtl number, $\mu c_p/k$
Q	Heat transfer rate, W
q	Heat flux, W/m^2
R	Thermal resistance, K/W
R_w	Wall thermal resistance $(D_o \ln(D_o/D_i)/2k_w)$, K/W

$r_{i,B}$	Inner radius of the boiler, m
$r_{o,B}$	Outer radius of the boiler, m
Ra	Rayleigh number, GrPr
Re	Reynolds number, $u_\infty D_o/\nu_\infty$
$\widetilde{Re}$	Two-phase Reynolds number, $u_\infty D_o/\nu_L$
T	Temperature, °C
T_f	Film temperature, °C
$T_{i,B}$	Inner wall temperature of the boiler, °C
$T_{o,B}$	Outer wall temperature of the boiler, °C
T_∞	Ambient temperature, °C
$\bar{T}$	Average temperature, °C
u	Velocity, m/s
u_∞	Vapor velocity, m/s
U_o	Overall heat-transfer coefficient, W/m^2-K
X	Parameter, $D\nu^{1/3}/Zk_L$
Y	Parameter, $\nu^{1/3}[1/U_o - R_w]$
Z	Sieder-Tate parameter, $Re^{0.8}Pr^{1/3}(\mu/\mu_w)^{0.14}$
β	Expansion coefficient of air, K^{-1}
μ	Dynamic viscosity, N-s/m^2
ν	Kinematic viscosity, m^2/s

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I. INTRODUCTION

A. BACKGROUND

As combat systems aboard naval surface ships continue to grow in importance, size, and weight, the feasibility of their installation aboard lightweight vessels can only be realized by reducing other major shipboard weight requirements. A significant achievement in reducing main propulsion weight was reached with the advent of gas-turbine propulsion plants, of which the majority of our new combatants will be powered. However, for the remaining capital ships and submarines to be constructed using either conventional or nuclear steam systems, power plant weight reduction can only be realized by increasing the effectiveness of the individual plant components and thereby reducing their size. Plans call for future installation of Rankine-cycle waste-heat recovery systems even on those ships with gas-turbine propulsion, so significant weight reduction could also be realized there through the use of more effective systems.

Due to the nature of the condensing process, the greatest thermal resistance to condenser-tube heat transfer occurs on the tube side, and a thorough review of tube-side enhancement is presented by Bergles and Jensen [Ref. 1]. Internal enhancement of the tube without regard to the shell-side resistance problem, however, would be a wasted effort if improvements were made to the point where the external (shell-side) resistance became the controlling factor in the transfer of heat. Recent investigations into the shell-side condensing process and techniques to improve this process are thoroughly reviewed by Marto [Ref. 2]. Outside enhancement techniques include the use of low

integral fins, roped tubes, fluted tubes, and applied coatings to promote dropwise condensation.

Ongoing research is underway at the Naval Postgraduate School to further study the shell-side enhancement of marine condensers. An endurance apparatus is in operation to examine the dropwise-promoting effectiveness of various metallic and polymer coatings over prolonged periods of time. Reilly [Ref. 3] conducted a study of improvements using various spirally fluted tubes under filmwise condensation, and the effects of tube bundle inundation have also been studied by Kanakis [Ref. 4].

A test apparatus has been constructed by Krohn [Ref. 5] to systematically study steam condensation on a single horizontal tube. The apparatus is modeled after a similar design constructed by Rose [Ref. 6], but can also operate under the high-vacuum conditions found in marine condensers and without the presence of noncondensable gases. This test apparatus was instrumented and tested by Graber [Ref. 7], who determined the Sieder-Tate coefficient for the test tube length to be 0.029.

In experiments using low integral fins at Queen Mary College of London, Rose, et. al., [Ref. 6] obtained an optimum pitch of 2.0 mm (0.08 in.) for a given fin size of 1 mm (0.04 in) high and 0.5 mm (0.02 in) wide for tests conducted at one atmosphere. With this pitch, he reported vapor-side heat-transfer enhancements of 400% and 300% for heat fluxes of 0.3 MW/m^2 (9.51×10^4 $Btu/hr\text{-}ft^2$) and 0.8 MW/m^2 (2.54×10^5 $Btu/hr\text{-}ft^2$), respectively, and for a vapor velocity of 0.7 m/s (2.3 ft/sec). Further testing is needed to compare these results with similar fin geometries under vacuum conditions, while varying fin dimensions (height and width) in addition to the fin pitch.

B. OBJECTIVE

The main objectives of this research effort were, therefore, to:

1) ensure a vacuum-tight apparatus so that data could be taken at both atmospheric and vacuum conditions with no detrimental effects due to the presence of noncondensable gases;
2) take data for an instrumented smooth tube to verify the Sieder-Tate coefficient obtained by Graber;
3) take data for a smooth tube to check the reliabilty of the apparatus and the data-reduction procedures used; and
4) take data for six externally-enhanced tubes of various fin pitches to obtain the relative optimum pitch for a fixed fin geometry.

II. DESCRIPTION OF APPARATUS

A. SYSTEM OVERVIEW

The apparatus used for this research was essentially the same used in references 5 and 7, with several noted modifications. A schematic sketch of the system is shown in Figure 2.1. Steam was generated in a 304.8-mm (12-in) diameter Pyrex glass boiler by ten 4000-watt, 480-volt Watlow immersion heaters. Passing through a 304.8-mm (12-in) to 152.4-mm (6-in) reducing section, the steam travelled upward through a Pyrex section 2.44 m (8.0 ft) in length, around a 180-degree bend, and back down a straightening section 1.52 m (5.0 ft) in length before entering the stainless-steel test section. The condenser tube to be tested was mounted horizontally in the test section behind a viewport to permit visual observation of the condensing process.

Steam that did not condense on the test tube passed into a stainless steel auxiliary condenser, and all condensate was returned via gravity to the boiler. The auxiliary condenser was constructed of two 9.5-mm (3/8-in) water-cooled copper lines helically coiled to a height of 457 mm (18 in).

Cooling water for the test tube was provided by two centrifugal pumps connected in series. The water could be throttled from zero flow to 0.69 l/s (11 gpm). The maximum water velocity which could be obtained through the tube was 5.48 m/s (18 ft/sec). A continuous supply of tap water was used for cooling the auxiliary condenser. Throttling the flow of tap water through the condenser was the means used to vary the internal pressure of the test apparatus. The water flow through both the test tube and the auxiliary

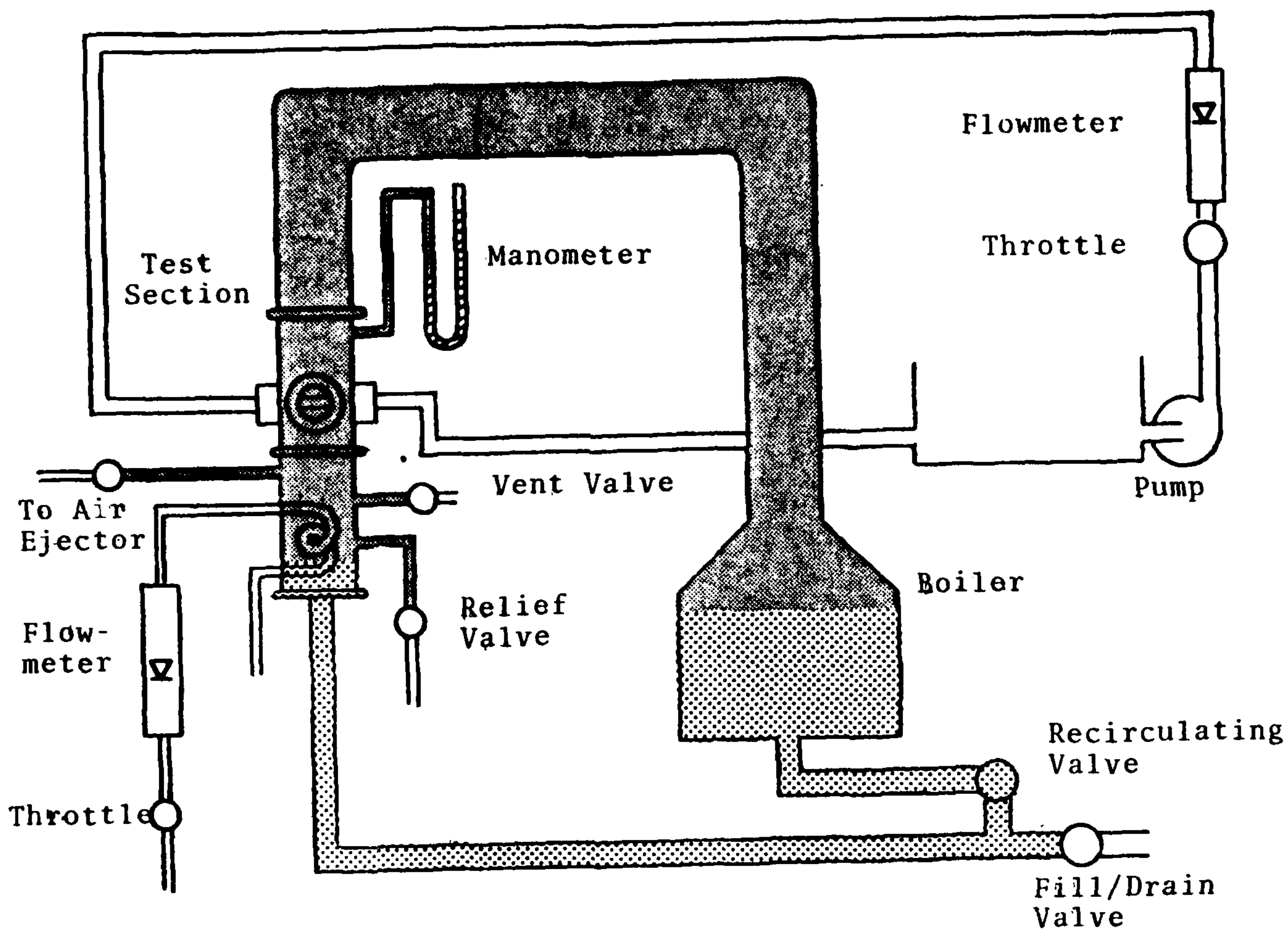

Figure 2.1 Schematic of the test apparatus.

condenser was regulated by 19.1 mm (3/4 in) diameter needle valves and measured by rotameters with full-scale ranges of 0.69 l/s (11 gpm).

An air ejector provided for removal of noncondensable gases from the auxiliary condenser through a 12.7-mm (1/2-in) line. The source for the air ejector was 1.1-MPa (160-psig) house-air supply.

B. SYSTEM INSTRUMENTATION

The input voltage through the heaters was varied through a panel-mounted potentiometer. 440-VAC line voltage was reduced by a factor of 100 when fed into a differential input precession voltage attenuator. The stepped-down voltage passed through a True-Root-Mean-Square converter stage on which the integrated period was reduced to about 1 ms. The output of the TRMS converter was then buffed and compared to a reference voltage from the potentiometer. The comparator output was fed to the control input of a Halmar silicon-controlled rectifier power supply which applied the actual voltage to the heaters. The TRMS converter output was also paralleled to a filter and then input to the data acquisition system. This input was proportional to the power supply output. A diagram of the system is shown in Figure 2.2.

The internal pressure of the system was measured manually by a U-tube, mercury-in-glass manometer graduated in millimeters. Unavoidably, steam could condense in the manometer. Therefore, the varying height of the water column in the manometer needed to be accounted for when measuring the system pressure.

Temperatures throughout the system were measured by copper-constantan thermocouples: six for the wall of a specially-constructed test tube, two for the steam, and one

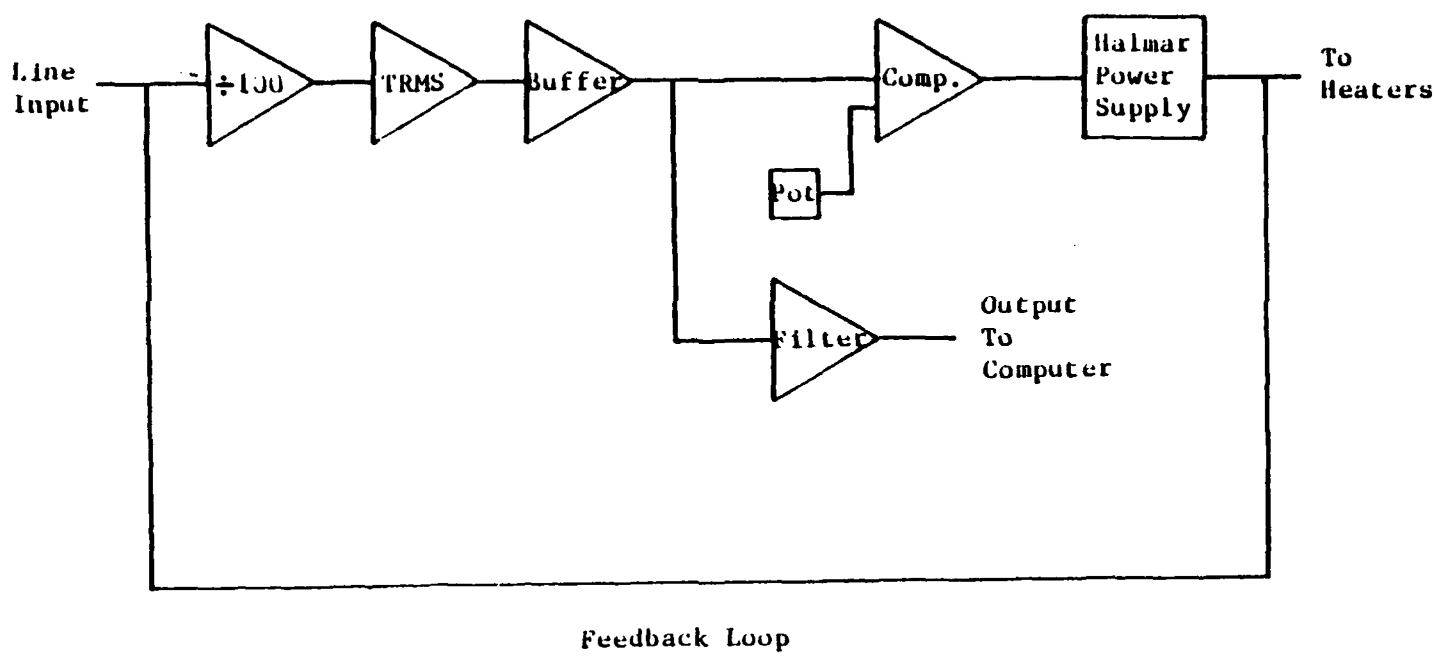

Figure 2.2 Line diagram of the power supply.

each for the cooling-water inlet, condensate return, and ambient. The calibration procedure for these thermocouples is described in Appendix A. The temperature rise through the test tube was measured by a Hewlett-Packard (HP) 2804A quartz thermometer.

All temperature measurements were fed directly into the data-acquisition system as described below.

C. DATA ACQUISITION

An HP 3497A Data Acquisition/Control Unit was used to monitor system temperatures. This was interfaced with an HP 9826A computer which served as a controlling unit through an interactive data-reduction program and user keyboard prompts. Raw data gathered by the data-acquisition system were stored on computer disks for later reduction and evaluation.

D. SYSTEM MODIFICATIONS

1. Boiler

The fiberglass insulation was removed from the boiler to allow the operator to more easily monitor the water level. Although a closed-system design was used, it was still possible for steam to escape via the air ejector or through the relief valve [Fig. 2.1]. Calculations showed that the additional heat loss due to the removal of the insulation was minimal [App. B], and the author felt this loss was much more acceptable than risking damage to the immersion heaters through a low-water casualty in the boiler.

2. Condensate Piping

As originally designed, draining the system required breaking down the condensate piping. While this was not a daily occurrence, the procedure was inconvenient and there existed also the possibility of losing the vacuum integrity of the system each time it was done.

To avoid these problems, the existing fill-line valves were rearranged as shown in Figure 2.1. This arrangement also added two additional features to the system:

1) the fill/drain valve could be opened during operation to drain any heavy particulate matter from the system - similar to the "bottom blow" procedure used on Naval boilers; and

2) after extended periods of inactivity while opened to the atmosphere, the entire system could be given a thorough steam-cleaning by following the procedures outlined in Appendix C.

3. Vent Valve

The modification of the condensate return piping necessitated the addition of a vent valve for use when filling or draining the system. A 4.3-mm (0.17-in) needle valve was installed on the 101.6-mm (4-in) flange of the test section. This valve would also serve as the tap for the proposed sampling of noncondensable gas concentrations in the system.

4. Manometer Line

The original system design used a 6.4-mm (1/4-in) stainless steel tube angled down to the mercury manometer. During this thesis, the manometer was raised to eye level to facilitate easier and quicker reading. Replacement of the

stainless-steel line by a 12.7-mm (1/2-in) copper tube reduced the possibilty of error caused by water slugs building up in the smaller diameter tube. The more workable copper was chosen over stainless steel to reduce the stiffness of the connecting line. This was necessary to eliminate leakage in this part of the apparatus as explained in Section II.E.

5. Pressure Transducer

As an alternative to the manometer, a Celesco strain-gage pressure transducer was installed on the test section flange next to the vent valve. The calibration line for the transducer is shown in Figure 2.3. The author felt, however, that the reliability of this measurement would not be high enough until a second, more accurate transducer was installed. Once incorporated into the system, though, these transducers would provide automatic input to the data acquisition system, eliminating the requirement to manually enter the manometer reading into the data-reduction program.

6. Relief Valve

As originally designed, a 6895-Pa gage pressure (1.0-psig) relief valve was installed beneath a 1.0-m (39.4-in) length of 12.7-mm (1/2-in) stainless-steel piping. Steam which condensed and became trapped in this piping would open the valve at a water-column height of only 0.70 m (27.6 in). Once opened, a back-pressure of 0.14 MPa gage (20 psig) was required to reseat the valve - something unobtainable even with an absolute vacuum on the inlet side of the valve. To avoid this problem, the valve was raised in the line to a point only 76 mm (3.0 in) below the outlet from the auxiliary condenser section and was replaced by another 6895 Pa gage pressure (1.0-psig) relief valve which reseated at only 0.04-MPa gage (6-psig) back-pressure.

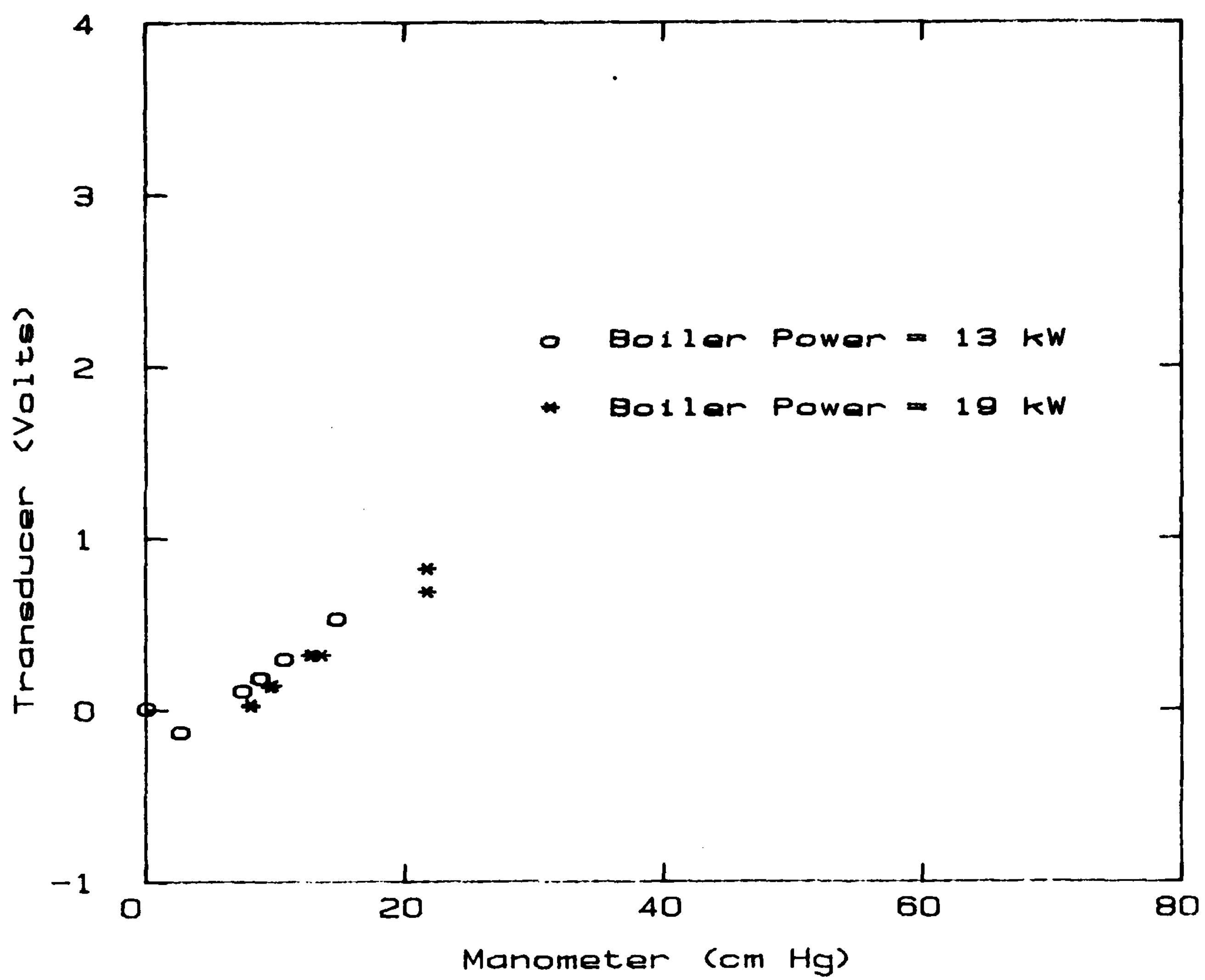

Figure 2.3 Calibration of the pressure transducer.

7. Steam-temperature Probe

The steam temperature probe was located directly above the test tube and shared the same inlet to the test section as the manometer line. When drawing a high vacuum, this arrangement allowed water which had collected in the manometer to be drawn back into the test section where it would flow down the probe and onto the tube. To prevent this water and any contaminants picked up in the manometer from being deposited on the tube, the probe was bent so that it was offset from the center of the test tube.

8. Cooling Water System

A second centrifugal pump was added in series to the one already installed. This pump boosted the maximum cooling water velocity through the test tube from 3.96 m/s (13 ft/sec) to 5.48 m/s (18 ft/sec).

The 10.55 kW (3 Ton) air-conditioning unit used with the cooling water system would energize at a water temperature of 17 °C (62.6 °F) and secure when the temperature was reduced to 13.4 °C (56.1 °F). Therefore, for a given steam temperature of 50 °C (122 °F) around the tube, the log-mean-temperature difference would vary by as much as 11%. But the measured temperature rise of the water through the tube showed very little change. To avoid this transient problem, the air-conditioning unit was not used, and instead fresh tap water was continuously fed to the sump while an equal amount of water was being drained, maintaining a constant sump level. This method provided a constant-temperature supply of cooling water to the inlet side of the test tube.

It should be pointed out that, while the duty cycle of the air-conditioning unit was a function of the thermostat used, a more sensitive thermostat would require the

use of a more expensive cooling device than a commercial air conditioner. An alternative solution would be to install a much larger sump in the system.

9. Thermopile

Since the temperature rise of the cooling water through the tube was a critical measurement in the experiment, a 10-junction thermopile was added to measure this temperature rise in addition to the quartz thermometer. As will be explained in Section V.A.3, however, problems arose with the thermopile, and it could not be accurately used during this thesis.

B. VACUUM INTEGRITY

One of the objectives of this thesis was to ensure a vacuum-tight test apparatus to eliminate the presence of any noncondensable gases and their detrimental effects on the condensing process. A standard of no more than a 5.0-mm mercury (0.10-psi) loss over a 24-hr period was considered to be an acceptable tolerance, but obtaining a leak rate within this tolerance proved to be the most time-consuming effort during the research.

Due to the construction of the apparatus and nature of the experiment, most leak-detection methods could not be used. A sealing substance could not be used without risking contamination of the interior of the apparatus which might prohibit filmwise condensation on the test tube.

Initially the system was pressurized and the standard soap-solution test was used to locate leaks. Once pressurized, a liquid-soap solution was applied to each external joint or fitting where a leak could be present. The higher pressure air inside the apparatus would escape through any leaks and produce bubbles on the applied soap film.

However, the maximum pressure which the Pyrex glass members could tolerate was only 0.074 MPa gage (10.7 psig), and for safety reasons the author chose not to pressurize the system to more than 0.034 MPa gage (5.0 psig) - a pressure difference between the atmosphere and the apparatus of only 0.040 MPa (5.8 psi). The numerous external valves and fittings prohibited the use of an evacuated hood to achieve a greater pressure difference.

A similar test could not be used to locate any vacuum leaks which were not present when the system was under a positive pressure, as the apparatus was not large enough to permit the application and observation of a soap solution on the interior.

In another attempt to locate the leaks, a National Research Corporation (NRC) 101.6-mm (4-in) vacuum pumping system was connected to the apparatus. This pumping system included a Welch model 1376M mechanical pump and a model NHS-4 diffusion pump. An NRC model 521 thermocouple gage was also connected to the test apparatus and the entire apparatus was evacuated to 0.21 torr (4.1×10^{-3} psia). Acetone was sprayed around all flanges, fittings, and joints. A leak around any of these should have produced a rapid rise in the thermocouple reading, but this method also proved ineffective, probably due to the large size of the apparatus resulting in too great a mean free path for the acetone molecules to travel from the leak to the thermocouple.

The next alternative was to break the system apart into three main sections: the glass boiler and steam piping, the stainless-steel test section and auxiliary condenser, and the condensate return piping. The glass section was blank-flanged and evacuated to an absolute pressure of 0.033 torr (6.4×10^{-4} psia). The rate-of-rise measurement for this section showed a loss of only 0.48 mm of mercury (0.01 psi) over a 30-hr period. It was, therefore, concluded that any leak in the assembled apparatus was not from this section.

Once removed, the test section and the auxiliary condenser were blank-flanged, pressurized to 0.10 MPa gage (15 psig), and immersed in a large plexiglas tank filled with water. This test easily revealed a number of small leaks about the inlet side of the test tube and also around the plug which connected the condensate return piping to the base of the auxiliary condenser. Replacing an O-ring in the tube fitting and silver brazing the plug into place eliminated these leaks.

The same immersion test revealed small leaks in the joints of the condensate return piping. These leaks were eliminated by replacing all stainless-steel ferrules in the Swagelok fittings with teflon ferrules.

Once reassembled, considerable leakage was still indicated by a substantial overnight rise in the manometer level. The author felt confident that this leak was not in the main assembly of the apparatus, but was instead in the manometer assembly itself since it could not be pressurized for testing. As mentioned in section II.C.4, the stainless-steel line leading to the manometer was at this time replaced by a 12.7-mm (1/2-in) soft copper tube. This tube eliminated the need for two 90-degree elbows and three lengths of stainless steel tubing in the line - an assembly which proved too rigid to allow even the slightest misalignment into the manometer.

Upon completion of the installation of this assembly, the system was evacuated to an absolute pressure of 92.5 mm Hg and over a 24-hr period the mercury level rose to only 94.0 mm. This leak rate was well within the acceptable tolerance.

F. TUBES TESTED

1. Instrumented Tube

An instrumented tube was fabricated from a thick-walled copper tube with an inner diameter of 12.70 mm (1/2 in) and an outer diameter of 19.05 mm (3/4 in). The tube was cut into three sections into which six holes were drilled axially along the walls at equal spacings 60 apart. These passages were fitted with 0.094-mm (3/32-in) OD capillaries [Fig. 2.4] which were silver-soldered into place, and the three sections of tube were then soldered back into one piece. Thermocouples were fitted into the capillary sections to measure an average wall temperature.

By knowing the average wall temperature, the Nusselt number for the inside could be computed. By computing the gradient of the Nusselt number against the Sieder-Tate parameter, the inside coefficient could be obtained as the inverse of the gradient. Figure 2.5 shows a photograph of the instrumented tube with the installed thermocouples.

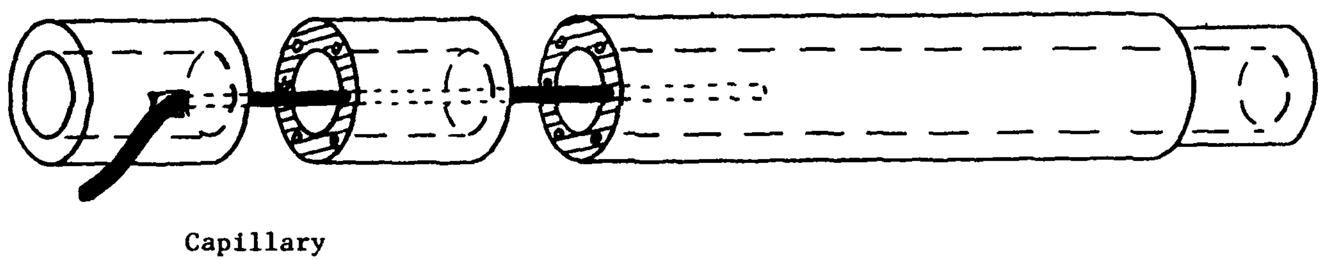

Figure 2.4 Schematic of the instrumented tube construction.

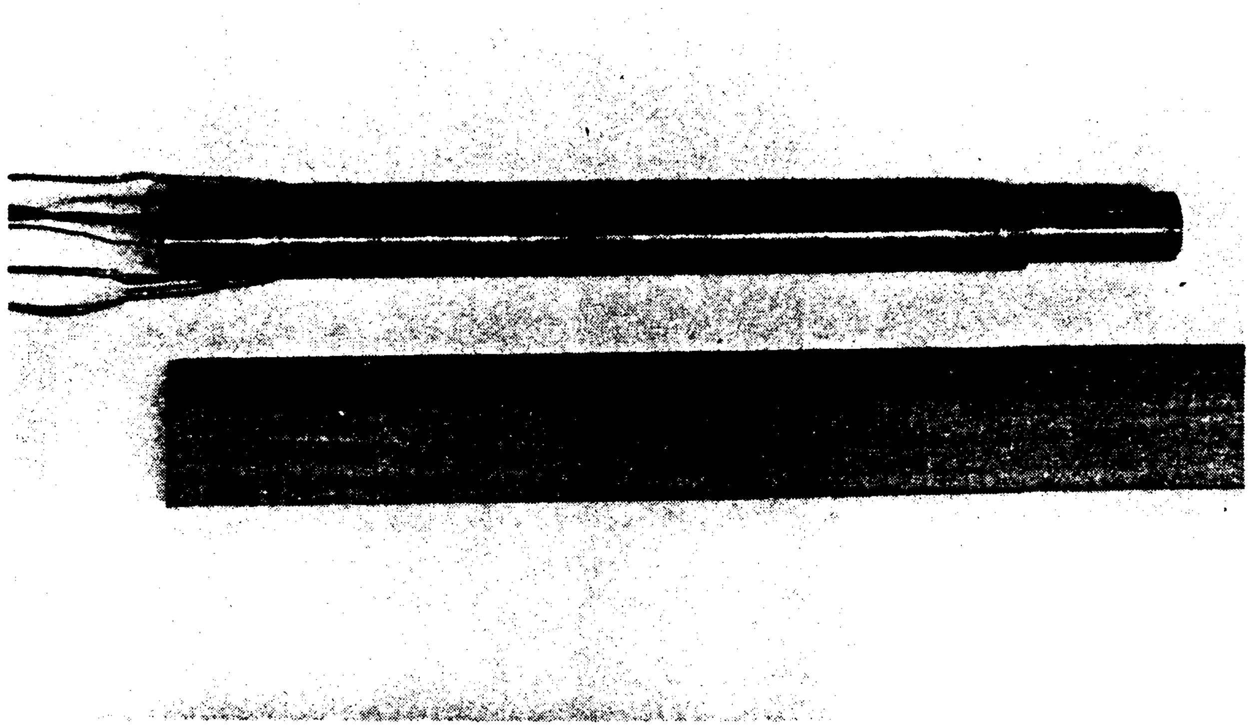

Figure 2.5 Photograph of the instrumented tube.

2. Smooth Tube

A smooth tube with no wall thermocouples was also tested to obtain the inside heat-transfer coefficient through the use of a modified Wilson Plot [Ref. 8]. Determination of the inside heat-transfer coefficient was critical to the experiment, as it was used to obtain the outside condensing coefficient for the smooth tube and all of the enhanced tubes.

3. Finned Tubes

To fulfill the main objective of this thesis, a series of six finned tubes was also tested [Fig. 2.6]. These tubes had the same overall dimensions as those above, but were enhanced with radial fins 1 mm (0.04 in) high and 1 mm (0.04 in) thick. Each tube had a different fin pitch and was tested to determine a relative optimum pitch. Fin pitches tested were 1.5, 2.0, 2.5, 3.0, 5.0, and 10.0 mm.

G. SYSTEM OPERATION

The tube to be tested was cleaned in a warm solution of Sparkleen and then rinsed with tap water, which produced a contaminant-free, wetted surface. The tube was then installed in the test section, care being taken not to touch or contaminate the condensing surface.

The system was brought to operating pressure by following the procedures of Appendix D, and data collection began when steady-state conditions were achieved. Steady-state conditions were determined by observing the steam temperature measured by the respective thermocouples. When their output voltage on the HP 3497A reached a constant value with fluctuations of only one or two microvolts, it was assumed that steady-state conditions existed in the test apparatus.

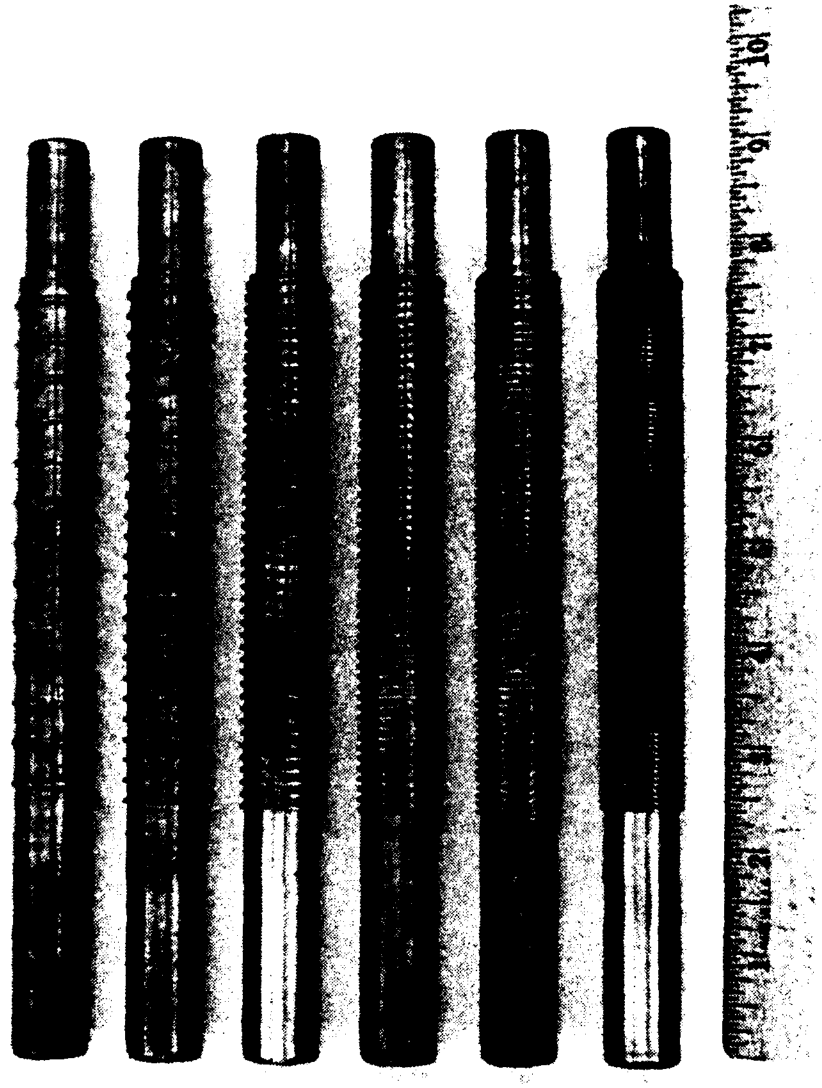

Figure 2.6 Photograph of the finned tubes tested.

Data sets were taken starting with a test-tube cooling water flow rate of 90% (which corresponded to a water velocity of 4.95 m/s or 16.2 ft/sec), ranging downward in decrements of 10% through a minimum flow of 20% (1.16 m/s, 3.8 ft/sec), and then upward from 25% to 85% in increments of 10%. After adjusting the flow rate, the temperature rise through the tube was monitored by observing the digital output of the quartz thermometer. When this rise became constant, another set of data could be taken. During data runs, a slight rise in pressure accompanied the decrease in the cooling water flow through the tube, a result of the reduced heat flux. Similarly, increasing the flow through the tube caused a slight decrease in the system pressure. This variance could be anticipated, and since data were to be collected at a constant pressure, it was easily compensated for by throttling the flow of cooling water through the auxiliary condenser one or two percentage points on the rotameter.

Something which could not be anticipated, however, were sudden fluctuations in the tapwater pressure to the auxiliary condenser which caused pressure changes of several millimeters of mercury in the system. To avoid this problem, the flow through the auxiliary condenser had to be continuously monitored, unless data were being taken late at night when there was no demand on the laboratory building's water supply. The test tube could be easily monitored through the viewport for confirmation of filmwise conditions. If there was any sizeable change to dropwise condensation on the tube, the data set was discarded and the procedure was repeated.

III. FILMWISE CONDENSATION

A. THE DROPWISE PROBLEM

It was essential during the course of this thesis to collect data under filmwise conditions. Numerous problems were encountered by Graber [Ref. 7] in avoiding the transition to dropwise condensation during operation, and his proposed solution was a vacuum-tight test apparatus. Since the tube surface would wet completely after installation, contaminants leaking into the system were possibly adhering to the surface and promoting the dropwise condensation.

However, even after obtaining a vacuum-tight apparatus, the author was still unable to maintain good filmwise condensation for more than two hours on a smooth tube. While this was enough time to collect a complete set of data for this tube, filmwise condensation lasted seventeen minutes at the most on any of the finned tubes, the average time being less than ten minutes. This was predictable - the corners of the fin/surface interfaces provided a better trap for contaminants and were harder to clean - but unacceptable.

The use of the steam-cleaning method described in Appendix C would thoroughly clean the tube so that complete filmwise condensation was re-established, but dropwise condensation would again become prevalent within minutes.

B. SOLUTION

Having eliminated the possibilities of installing a dirty tube or contamination due to leakage, the only reason for the dropwise problem had to be coming from outgassing of the nylon holders for the test tube. The outgassing rate for nylon was found to be almost two orders of magnitude greater

than the rate for Teflon [Ref. 9], Teflon being the same order as stainless steel. By pumping down the apparatus while it was hot, nylon molecules were being outgassed into the test section and were immediately being deposited onto the surface of the cooler test tube, resulting in inadvertant "sputtering" of the tube with a nylon coating and subsequent dropwise condensation. To eliminate the nylon interface with the interior of the test section, special stainless steel caps were manufactured to slip over the nylon holders.

Teflon bushings were fitted within the caps to insulate them from the the tube. Teflon had both a low thermal conductivity and a relatively low outgassing rate. Figure 3.1 shows a detailed sketch of the installation.

This configuration appeared to solve the problem of dropwise condensation. Although an actual endurance test was not conducted, the system was in operation intermittantly for over fifteen hours with the smooth tube and over four hours with each finned tube with no breakup of the filmwise condensation.

Once installed, this arrangement also eliminated the need for the tube-cleaning procedure recommended by Graber [Ref. 7], who felt that a strong cleaning solution of sodium hydroxide and ethanol was needed to decontaminate the surface. Only a warm solution of Sparkleen was used throughout the data-collection stage of this thesis.

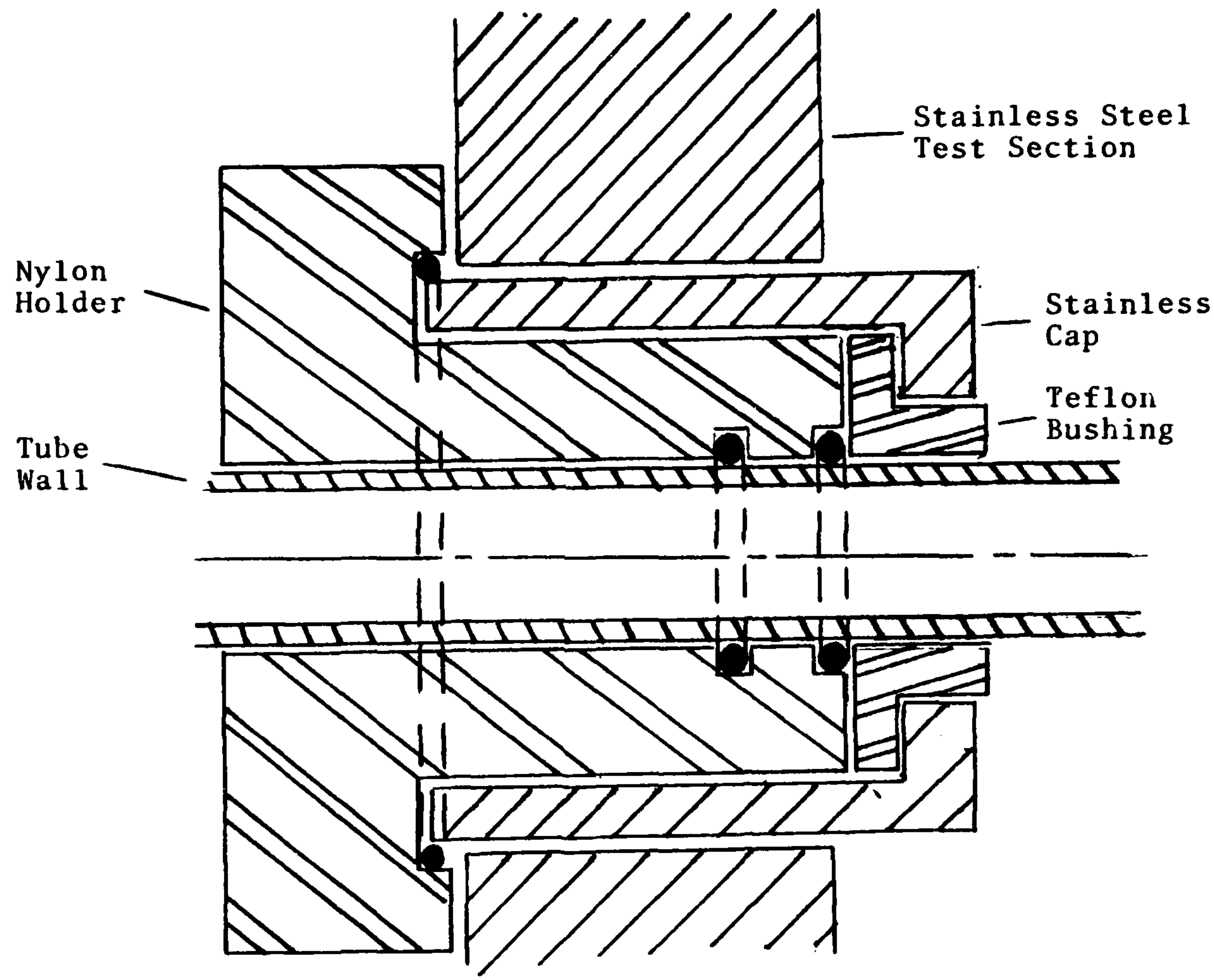

Figure 3.1 Cross-sectional view of the tube and holders.

C. VAPOR VELOCITY LIMITATIONS

To check the outside heat-transfer coefficient data with the Nusselt prediction, and also to obtain an accurate inside coefficient with the modified Wilson Plot, vapor velocities approaching zero were preferred. Due to the design of the system, however, the pressure drop to the auxiliary condenser required vapor flow past the test tube. This being the case, attempts were made to minimize this flow velocity by cutting down the power to the boiler and throttling back on the cooling water supply to the condenser. As vapor velocity was decreased, however, dropwise condensation again took place on the test tube. Under atmospheric pressure, this occurrence was at vapor velocities of about 0.5 m/s (1.6 ft/sec), and under vacuum operations it occurred at about 0.9 m/s (3.0 ft/sec). Apparently there still existed a sizeable rate of outgassing within the test section, those gases collecting about the test tube and interfering with the filmwise condensation process. This suspicion was confirmed when an increase in the vapor velocity eliminated the formation of drops on the tube.

IV. DATA REDUCTION

The data collected and stored on the computer disks reduced using the programs WILSON, SIEDER, and DRP. The programs were amenable to changes, which allowed the author to analyze and compare results while varying parameters within the programs. Stepwise reduction procedures for each program are listed below and the program listings are found in Appendix E.

A. PROGRAM SIEDER

1. Compute the average cooling water temperature.
2. Compute the average wall temperature.
3. Compute the cooling water velocity.
4. Compute the mass-flow rate of the cooling water.
5. Compute the heat transferred to the cooling water.
6. Compute the average inside wall temperature.
7. Compute the log-mean-temperature difference.
8. Compute the inside heat-transfer coefficient.
9. Compute the Nusselt number.
10. Compute the Sieder-Tate parameter.
11. Compute the inside coefficient.

B. PROGRAM WILSON

1. Assume a value for the Sieder-Tate coefficient.
2. Compute the Reynolds and Prandtl numbers for flow through the tube.
3. Compute the log-mean-temperature difference, heat flux, and overall heat-transfer coefficient for the tube.
4. Assume an outer tube surface temperature.

5. Compute the outside condensing coefficient using properties evaluated at the film temperature.

6. Compute the outer surface temperature and iterate steps 5 and 6 if not within 1%.

7. Assume a viscosity-correction factor for the Sieder-Tate equation of 1.0.

8. Compute the inside heat-transfer coefficient.

9. Compute the inner surface temperature.

10. Compute the viscosity correction factor and iterate steps 8 through 10 if not within 1%.

11. Compute the Sieder-Tate coefficient and iterate steps 2 through 11 if not within 0.5%.

C. PROGRAM DRP

1. Compute the average cooling water temperature.
2. Compute the cooling water velocity.
3. Compute the mass-flow rate of the cooling water.
4. Compute the heat transferred to the water.
5. Compute the log-mean-temperature difference.
6. Compute the overall heat-transfer coefficient.
7. Compute the wall resistance of the tube.
8. Compute the Reynolds number of the cooling water.
9. Compute the inside heat-transfer coefficient.
10. Compute the condensing heat-transfer coefficient.

V. RESULTS AND DISCUSSION

Numerous data runs were made using the procedure described in Section II.G. Time constraints, however, limited the number of repeat runs that could be made for this thesis. Primary concern focused on establishing a reliable, repeatable Sieder-Tate coefficient. Data were taken for all of the tubes at both atmospheric and vacuum (88mm Hg, 1.7 psia) conditions. Complete filmwise condensation was maintained for all data runs, and the mass concentration of noncondensable gases was held between 0% and -1% during all testing. The negative value was indicative of slight superheat in the system or an inaccurate manometer reading.

A. INSIDE HEAT TRANSFER COEFFICIENT

1. Instrumented Tube Results

Figure 5.1 shows the variation of the Nusselt number as a function of the Sieder-Tate parameter for the instrumented tube run at atmospheric pressure (run SDA7). This method yielded a Sieder-Tate coefficient of 0.035 on two separate data runs (SDA7 and SDA8). The same method under vacuum conditions yielded a coefficient of 0.037, which was also repeated (runs SDA5 and SDA6). The temperature distribution around the tube wall was symmetrical about the vertical plane passing downward through the centerline of the tube, and showed as much as a 16 C temperature drop from the top of the tube to the bottom.

2. Smooth Tube Results

Figure 5.2 shows the modified Wilson Plot for smooth-tube data collected at atmospheric pressure (run

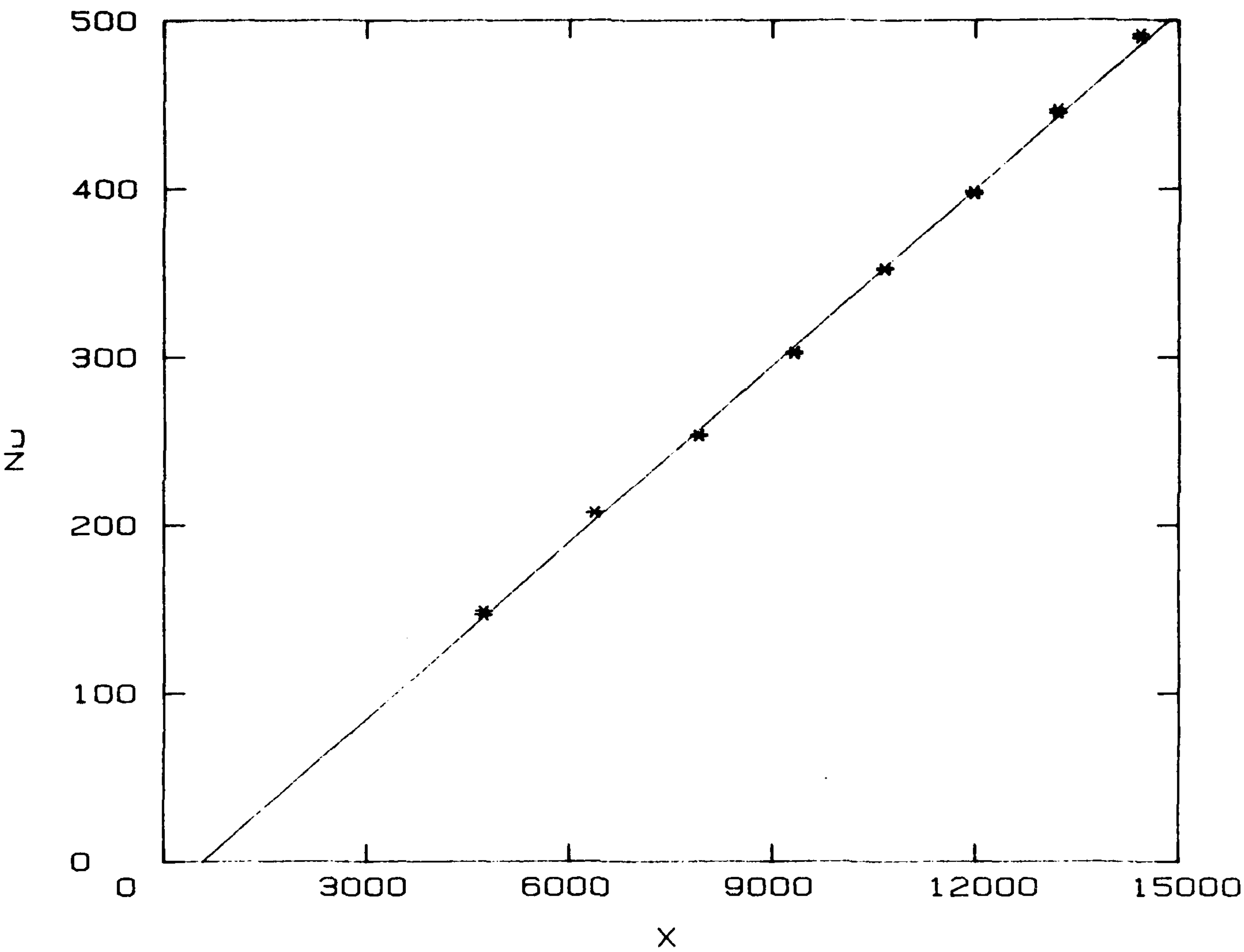

Figure 5.1 Inside Nusselt number plot for the instrumented tube.

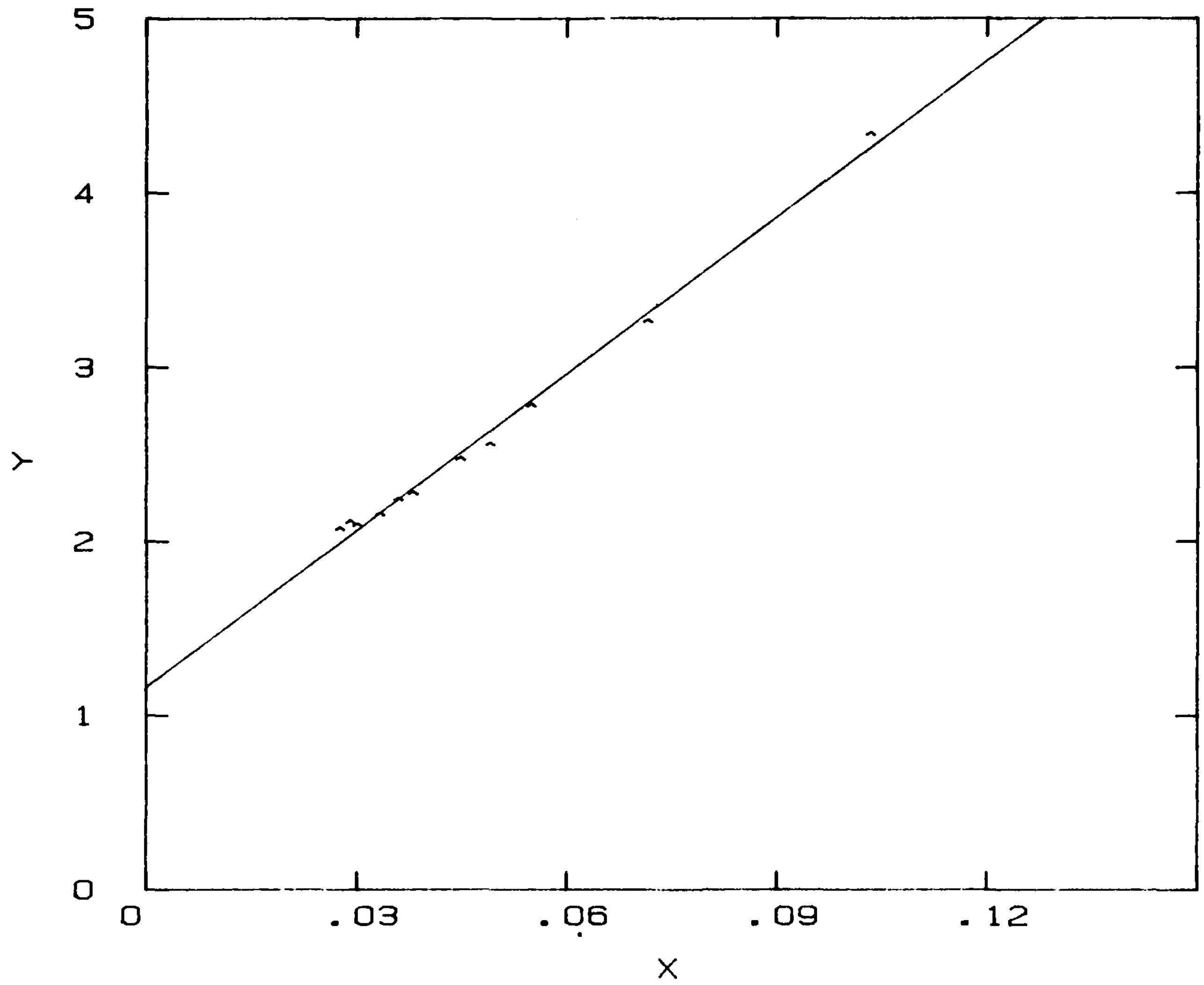

Figure 5.2 Wilson plot for the smooth tube.

OD12). This method produced a Sieder-Tate coefficient of 0.033 with an intercept of 1.16. A similar plot for vacuum conditions (run OD10) produced a coefficient of 0.036 and an intercept of 1.27. The Nusselt theory predicts an intercept of 1.53 but, as was noted in Section III.C., a finite vapor velocity past the tube was unavoidable in this research.

Figure 5.3 shows a plot of the Fujii [Ref. 10] correlation for the smooth-tube runs. This experimental correlation is to correct the Nusselt number for the effects of vapor shear on the test tube and is a plot of the equation:

$$Nu\widetilde{Re}^{-1/2} = 0.96F^{1/5}$$

The results obtained were slightly higher than those predicted using this correlation.

3. Discrepancies

The original Sieder-Tate equation [Ref. 11] for fully developed turbulent flow in a tube with an L/D ratio greater than 60 has a leading coefficient of 0.027, so a higher value for the shorter tube (L/D = 18) used for this research stands to reason. The data for the tubes appears at first inconsistent, with results of 0.033, 0.035, 0.036, and 0.037 - showing up to a 6% scatter from the mean. Both tubes, however, showed a larger coefficient when the test section pressure was reduced, which reduced the heat flux as well. Dropping the pressure from atmospheric to a high vacuum (88 mm Hg, 1.7 psia) reduced the heat flux by a factor of almost three [Fig. 5.4]. Stated another way, a low heat flux produced coefficients of 0.036 and 0.037, while a higher heat flux produced 0.033 and 0.035.

The author doubts the reliability of the inside coefficient obtained under vacuum conditions for two reasons:

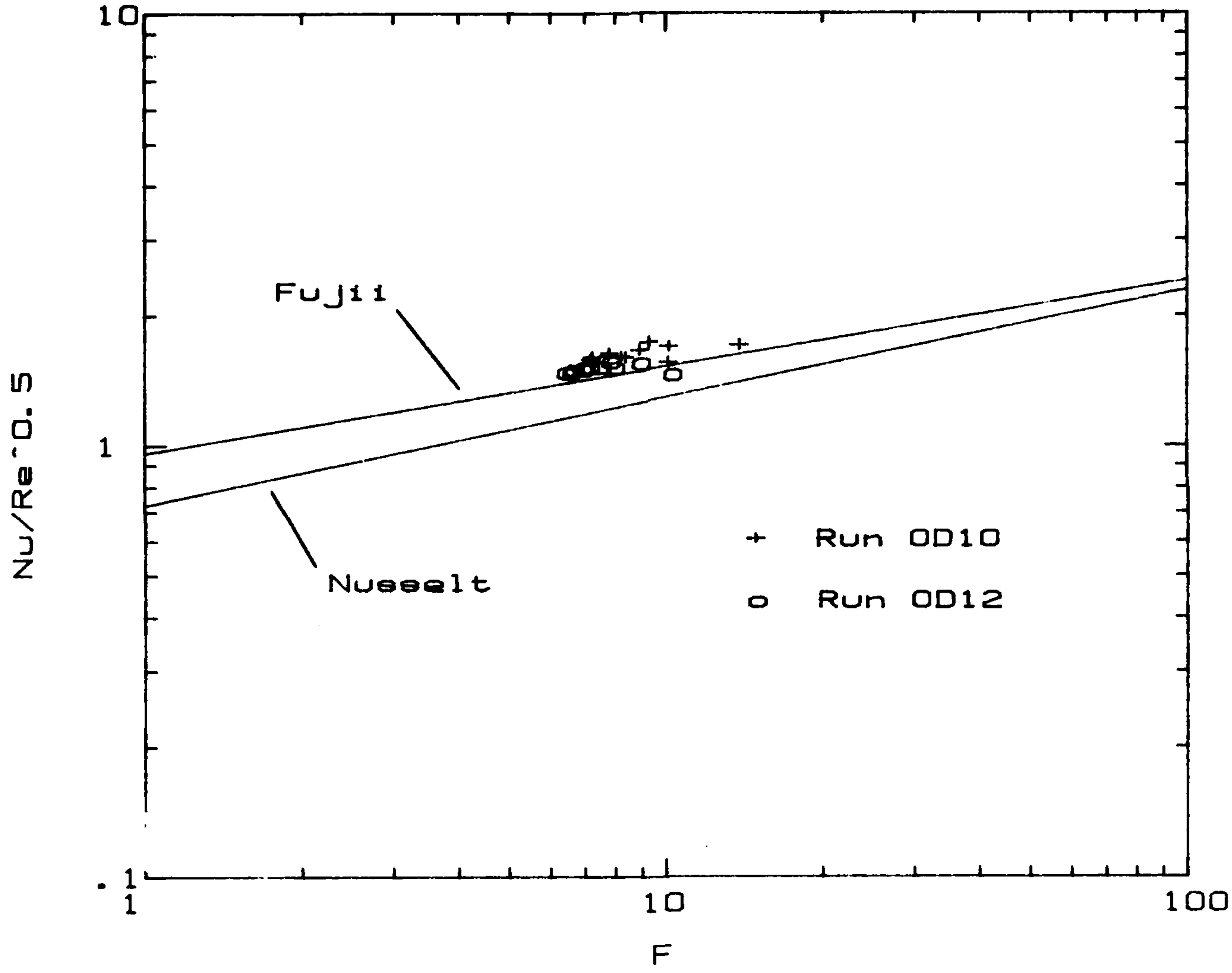

Figure 5.3 Fujii correlation [Ref. 10] for smooth-tube data.

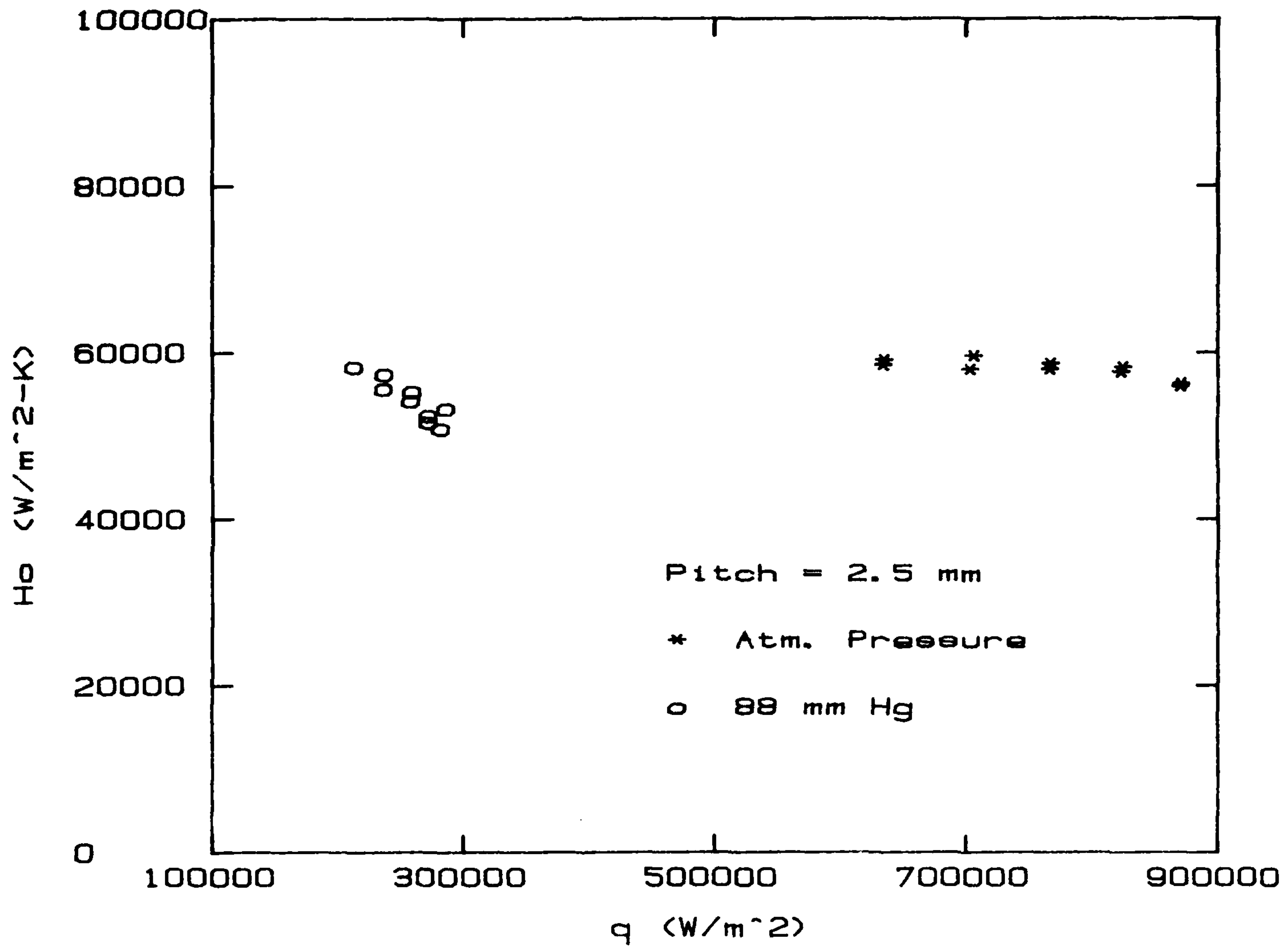

Figure 5.4 Relative heat fluxes for atmospheric and vacuum runs.

First, reducing the flow rate through the tube lowers the heat flux and increases the inside convective thermal resistance. Since the condensing coefficient is inversely proportional to the heat flux raised to the one-third power, the outside condensing resistance decreases. Because of this, the inside resistance becomes the dominant factor in the overall thermal resistance of the tube. Any error in measuring the inside heat transfer coefficient will greatly amplify the computed error in the condensing resistance. Thus, the condensing coefficient is highly sensitive to the accuracy of the inside coefficient, particularly at low water velocities (and corresponding heat fluxes).

Second, the test apparatus was subject to radio-frequency (RF) interference from the power supply. As the power was cut back to lower the heat flux, the silicon controlled rectifier chopped the input signal proportionally and emitted the chopped portion as RF energy. Despite efforts to shield the cabling to the data-acquisition system, it still captured the RF signal with unacceptable results, and the thermopile was experiencing instantaneous fluctuations of several hundred microvolts. Increasing the power supply, however, decreased the errant signal until, at the maximum power input used for the high heat flux measurements, the thermopile showed a near-steady temperature difference that was within 0.1 °C of the quartz thermometer.

For these reasons, the Sieder-Tate coefficients obtained from the low heat-flux runs were discarded. Averaging the coefficients found from both measurements for the high heat flux case yielded a coefficient of 0.034 ± 0.001.

B. FINNED TUBES

Figure 5.5 shows a relative plot of the outside condensing coefficient for all six finned tubes compared with smooth tube results and the Nusselt line. Figure 5.6 shows the same results corrected for area increases due to finning. These data were computed using the leading coefficient on the inside of 0.034 obtained in the previous section.

All tubes tested show good enhancement over the smooth tube. Notice the increase of the smooth tube over the Nusselt line - a result of the inherent vapor shear in the test section. The increased scatter in the lower heat-flux range is again a function of the increased significance of errors in measuring the inside thermal resistances. The plotting program used neglected ordinate values below zero or greater than 10^5, so the scattering in this portion of the plot is actually worse than it appears. Figure 5.7 is a plot of the values obtained for the outside heat transfer coefficients of the six finned tubes for a constant heat flux of 250,000 W/m^2 (79,000 $Btu/hr\text{-}ft^2$) and a pressure of 88 mm Hg (1.7 psia). This plot more clearly shows the optimum pitch of 2.5 mm.

The heat-transfer characteristics for any tube will be enhanced by the addition of fins. In the case of purely convective heat transfer, the enhancement is a function of the increased surface area exposed to the fluid medium.

Filmwise condensation, however, is dissimilar in that the build-up of a condensate film acts as an additional thermal resistance for the heat-transfer process. The objective of tube enhancement, therefore, is to decrease this film thickness. The surface tension forces in the condensate tend to draw the liquid toward the fins, leaving the tube surface with a thinner film. The thinner film results in a higher heat-transfer coefficient. [Ref. 12].

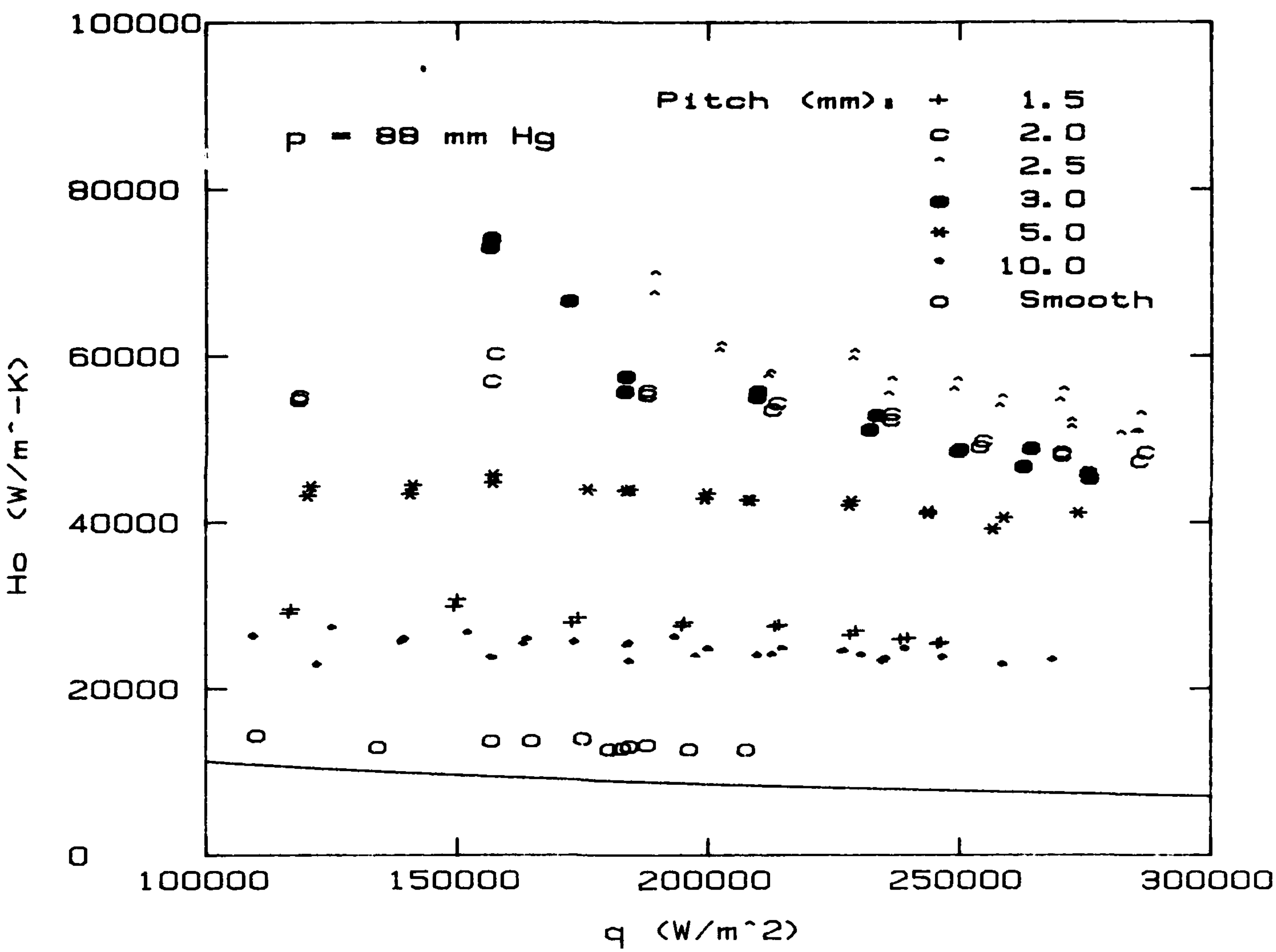

Figure 5.5 Comparison of finned tubes with smooth-tube performance.

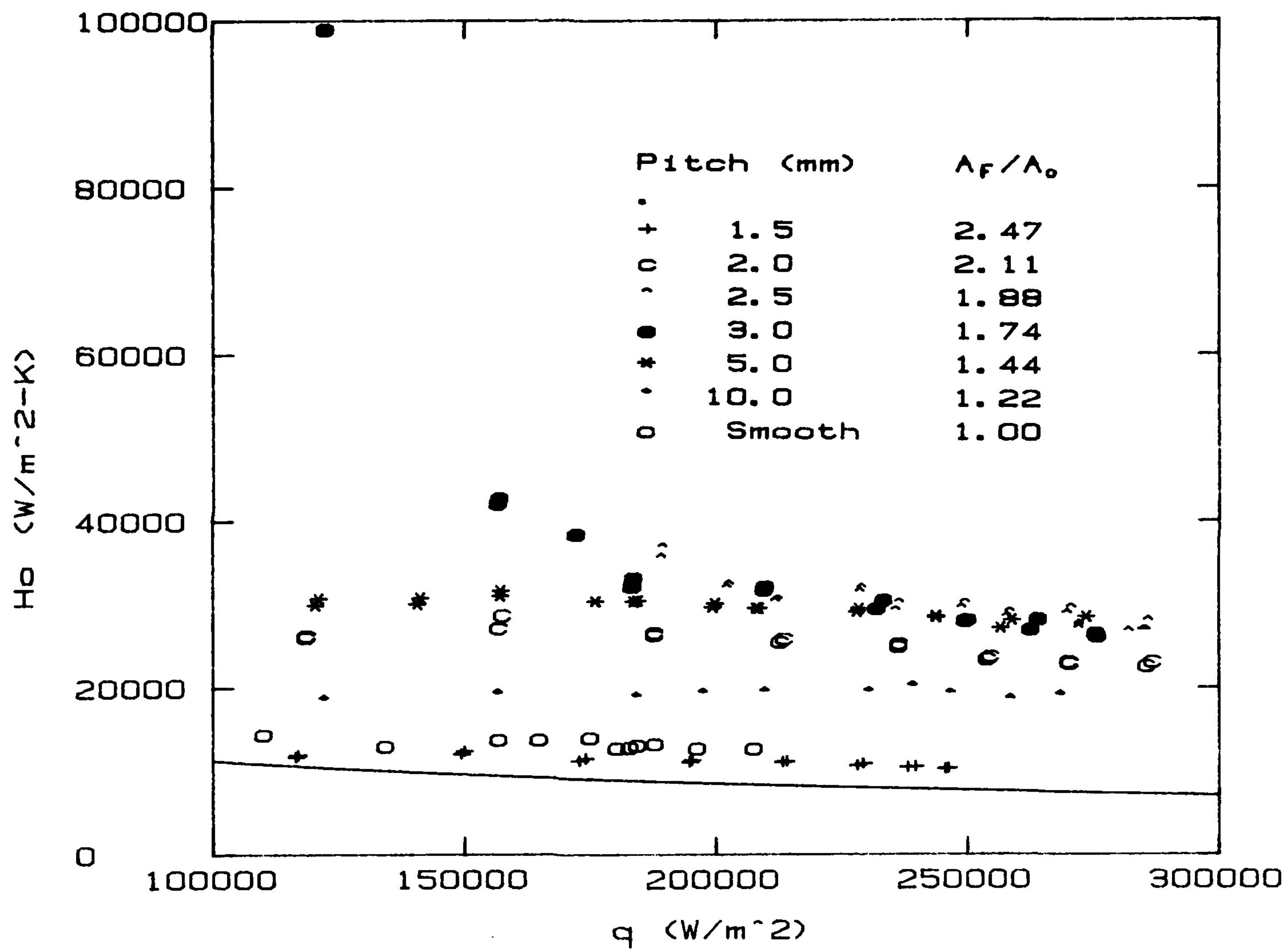

Figure 5.6 Outside condensing coefficients corrected for area.

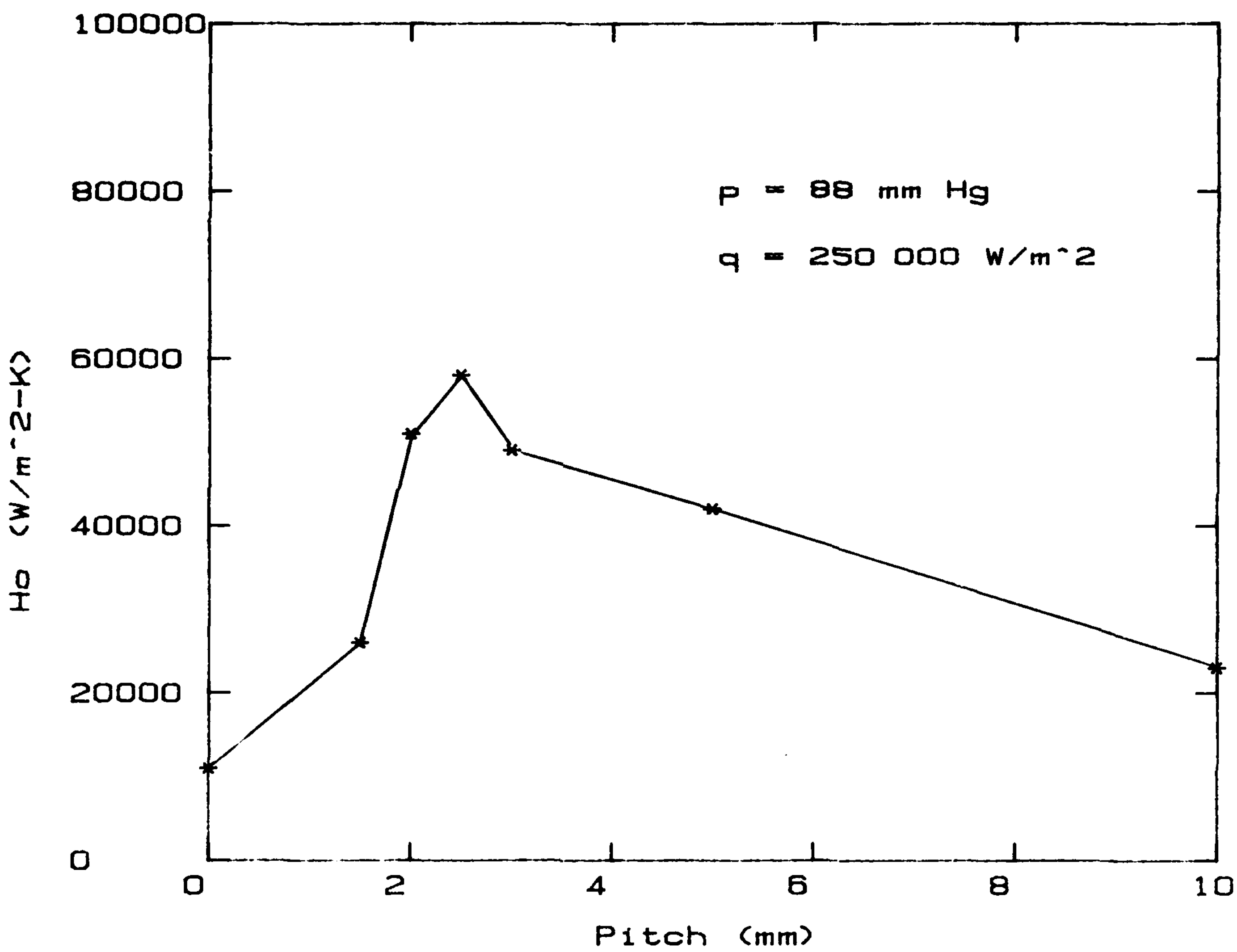

Figure 5.7 Variation of condensing coefficient with fin pitch.

The optimum pitch found in this research increases the surface of the condenser tube 88%, but condensing heat-transfer coefficients for that pitch were enhanced by as much as 330%.

The optimum pitch serves as the right trade-off between the attractive forces of the fins on the condensate and the channel area between the fins to drain the condensate from the tube. A pitch smaller than the optimum has too narrow a gap between fins to efficiently allow condensate run-off. This is because the condensate drawn to adjacent fins only combines to create a thicker film as shown in Figure 5.8.

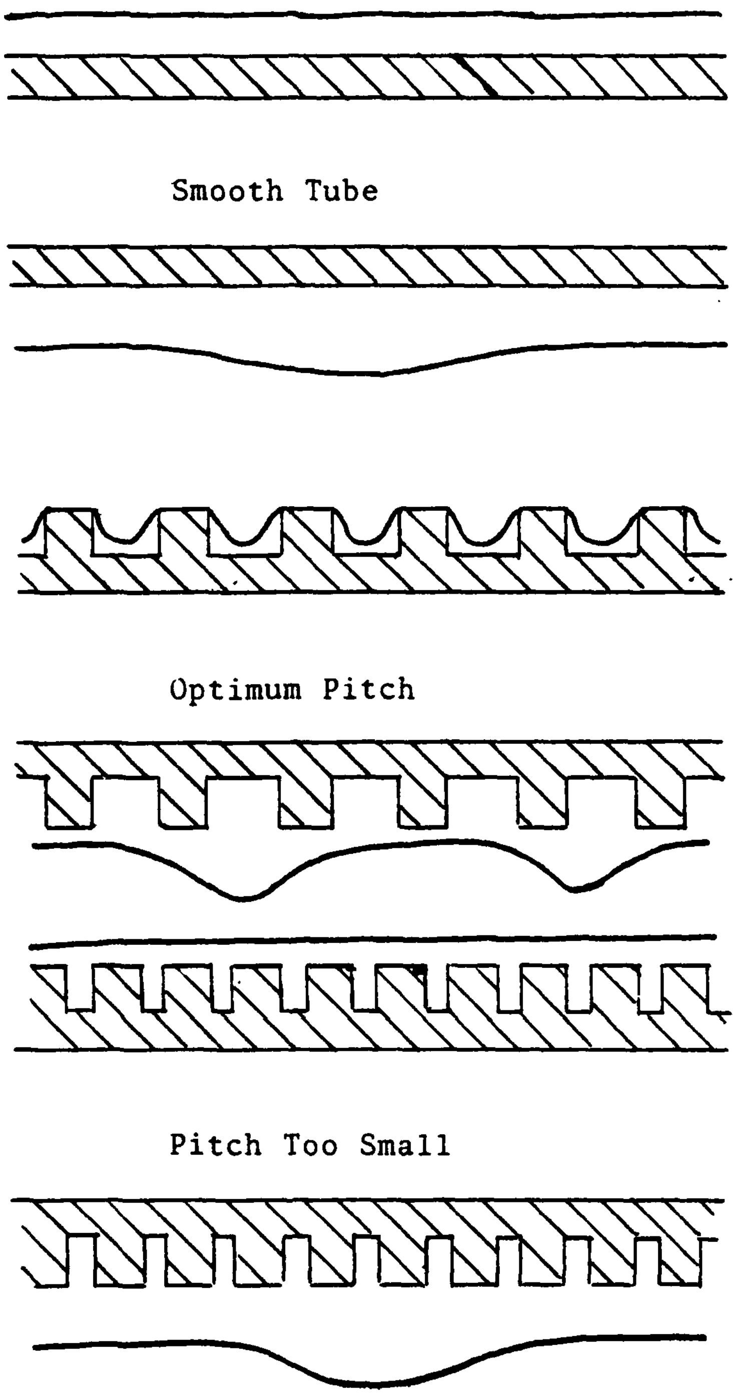

Figure 5.8 Sketch of the effect of finning on condensation.

VI. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

1. The test apparatus successfully operates under vacuum conditions with no degrading effects caused by the presence of noncondensable gases.

2. The Sieder-Tate coefficient was determined to be 0.034 ± 0.001 using both an instrumented smooth tube and the modified Wilson plot technique.

3. An optimum fin pitch of 2.5 mm was found for the finned tubes tested.

4. Heat-transfer enhancements up to 300% were realized while the increase in the tube outer surface area (due to finning) was only 88% over the smooth tube.

B. RECOMMENDATIONS

1. Install a second, more reliable pressure transducer to replace the manometer.

2. Install a larger cooling-water sump to eliminate use of the once-through system from the fresh-water tap.

3. Collect data using an insert for the test tube to decrease the internal convective resistance and, thereby, decrease the uncertainty in the calculated condensing coefficient.

4. Take data for the finned tubes while varying fin height and thickness (as well as pitch).

APPENDIX A

THERMOCOUPLE CALIBRATION

1. EQUIPMENT USED

a. Thermocouple Wire

Copper-constantan, 0.245-mm (0.01-in) Teflon-coated wire was used for all thermocouples.

b. Calibration bath

A Rosemont Engineering Model 913A calibration bath was used. A schematic representation of the bath is shown in Figure A.1.

1) Heating: Electrical

2) Cooling: Liquid Nitrogen

Note: Once a desired temperature is reached, the temperature is held constant by rapid cycling between heating and cooling. The bath is rated for temperature fluctuations of less than 0.01°C.

c. Thermocouple readout

An HP 3054A Data Acquisition/Control System was used to obtain data. Resolution of the acquisition system was 1 μV.

d. Bath temperature measurement

A platinum resistance thermometer with an accuracy of 0.01 C was used.

2. PREPARATION

a. Procedure

The instrumented tube (with the wall thermocouples installed) and the steam thermocouples were immersed in the bath as well as the probes for the quartz thermometer.

b. Analysis

The computer program TCAL was used to monitor and store all thermocouple readings on a disk. A listing of the program is located in Appendix E.

3. CALIBRATION PROCEDURE

a. The bath temperature was set at about 10 °C.

b. When the bath temperature reached steady state, its value was entered into the computer.

c. The computer automatically recorded and printed all thermocouple readings.

d. The bath temperature was raised in increments of 10 C to 90 °C and steps b and c were repeated for each increment.

4. CALIBRATION CURVES

a. A least-squares method was used to generate a polynomial of the form:

$$D_T = a_0 + a_1 T + a_2 T^2$$

where: D_t is the difference between the bath and thermocouple temperatures, and

T is the value of the thermocouples obtained using the seventh-order polynomial fitted for the Type T thermocouple wire used. This polynomial is listed in the beginning of the program TCAL.

b. Coefficient values obtained were:

$$a_0 = 4.7338 \times 10^{-3}$$

$$a_1 = 7.6928 \times 10^{-3}$$

$$a_2 = -8.0779 \times 10^{-5}$$

c. A plot of the curves is found in Figure A.1. The curve for the wall thermocouples gives a different reading due to the thermal conduction of the air temperature through the tube. The data used for calibration did not include this average value. Only the value obtained for the two steam thermocouples was used for all of the thermocouples.

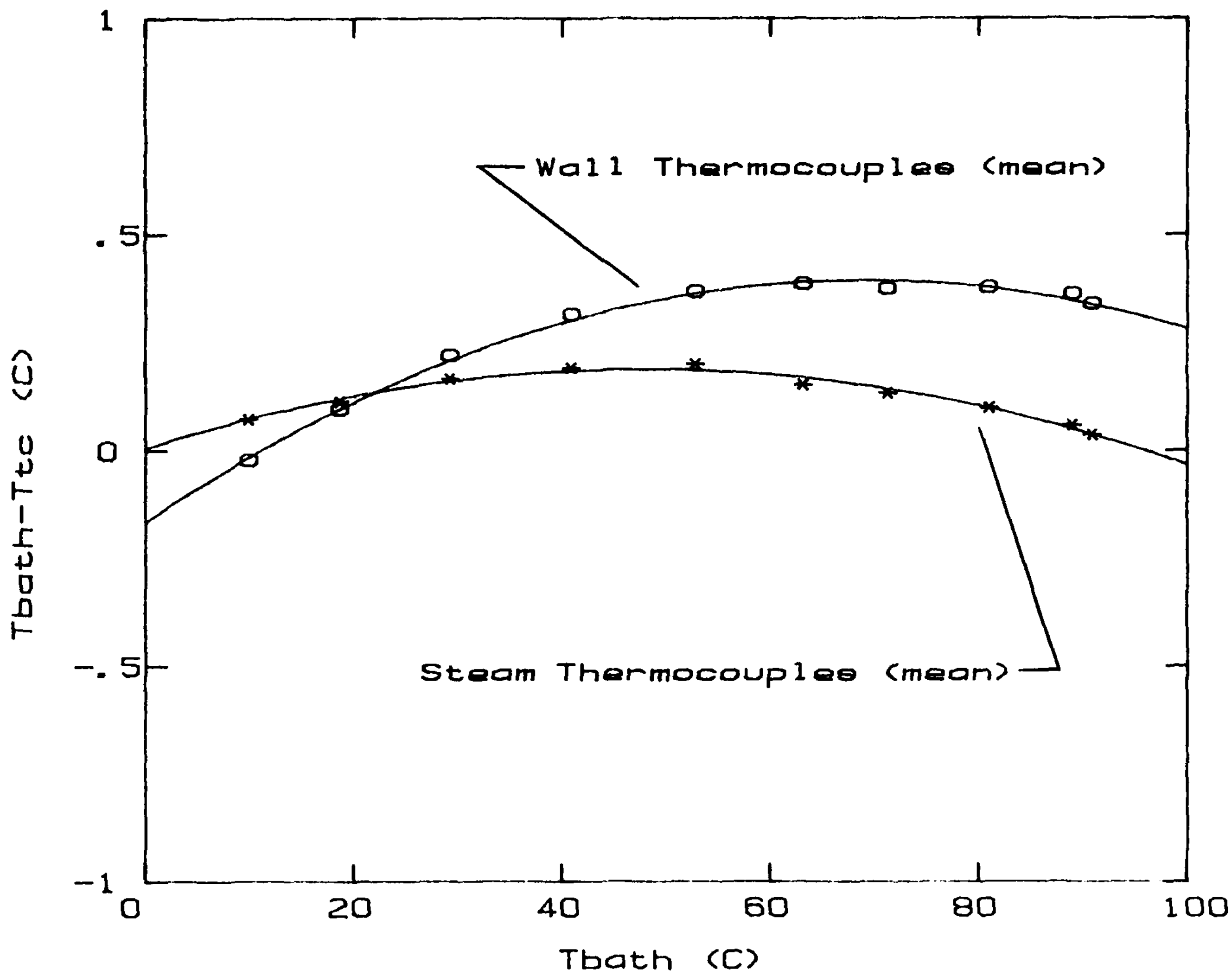

Figure A.1 Calibration curve for the thermocouples.

APPENDIX B
SAMPLE CALCULATIONS

1. HEAT LOSS

A set of calculations was performed to estimate the heat loss of the apparatus due to natural convection. These calculations were performed for two main sections: the boiler (with and without insulation) and the piping to the test section. The minimum power input used during the thesis was 17 kW.

a. Boiler (without insulation)

1) Given the following dimensions and properties of the boiler section:

$r_{i,B} = 0.1524$ m

$r_{c,B} = 0.1561$ m

$L_B = 0.4064$ m

$k_c = 1.4$ W/m-K

2) Given the following temperatures:

$T_{i,B} = 100°C$

$T_{c,B} = 95°C$

$T_\infty = 25°C$

$T_f = (95+25)/2 = 60°C$

3) Given the following properties of air at the film temperature:

$k_A = 28.74 \times 10^{-3}$ W/m-K

$Pr = 0.702$

$\nu = 19.21 \times 10^{-6}$ m^2/s

$\beta = 0.003$ K^{-1}

4) Compute the Grashof Number for the boiler assuming laminar conditions ($Ra < 10^9$):

$$Gr_B = g\beta(T_{o,B} - T_\infty)L^3/\nu^2$$

$$Gr_B = 3.7 \times 10^8$$

5) Compute the Rayleigh Number for the boiler:

$$Ra_B = Gr\,Pr$$

$$Ra_B = 2.6 \times 10^8 \qquad (< 10^9)$$

6) Determine the applicability of a flat-plate analysis according to the method of Sparrow and Gregg [Ref. 13]

$$L/r_{o,B} < (0.15/\sqrt{8})Gr^{1/4}$$

$$2.60 < 7.36$$

8) Compute the average Nusselt Number (via flat-plate analysis):

$$\overline{Nu} = [0.825 + 0.387Ra_B{}^{1/6}/[1+(0.492/Pr)^{9/16}]^{8/27}]^2$$

$$\overline{Nu} = 81.3$$

9) Compute the external heat-transfer coefficient:

$$\bar{h}_o = \overline{Nu}\,k/L$$

$$\bar{h}_o = 5.75 \text{ W/m}^2\text{-K}$$

10) Compute the external convective thermal resistance:

$$R = 1/(h_o 2\pi r_{o,B} L_B)$$

$$R = 0.436 \text{ K/W}$$

11) Calculate the wall resistance:

$$R_w = \ln(r_{o,B}/r_{i,B})/2\pi k_c L_B$$

$$R_w = 0.007 \text{ K/W}$$

12) Neglecting the wall resistance, calculate the heat loss from the boiler:

$$Q_B = (T_{i,B} - T_\infty)/(R + R_w)$$

$$Q_B = 169.3 \text{ W}$$

b. Boiler (with insulation)

$$Q_B' = 29.2 \text{ W}$$

c. Piping

$$Q_P = 65.0 \text{ W}$$

d. Total (worst case)

$$Q = Q_B + Q_P$$

$$Q = 234.3 \text{ W} \qquad (\ll 17000 \text{ W of input power})$$

APPENDIX C

STEAM-CLEANING PROCEDURE

Note: The procedures listed here provide an excellent method of cleaning the apparatus, but will cause the walls of the apparatus to heat to temperatures over 100 C (212 F). Once this happens, several hours are required before the walls can cool down such that they won't superheat the steam generated during an experimental run. Therefore, use this method only prior to operating at atmospheric pressure or when the system is badly contaminated.

1. Ensure the water level in the boiler is at least six inches above the upper ends of the heaters.
2. Remove the thermopile from the inlet side of the test section.
3. Energize the power supply and adjust the rheostat until the voltmeter reads about 100 V.
4. Close the recirculating valve.
5. Open the fill/drain valve.
6. Once vapor begins exiting the fill/drain line, allow the system to steam for several minutes.
7. To maximize the steam flow through the test section, fully open the throttle to the auxiliary condenser.
8. When done, simultaneously close the drain/fill valve and open the recirculating valve.
9. Circulate cooling water through the test tube and check for the presence of any dropwise condensation.
10. Reinstall the thermopile.

APPENDIX D

SYSTEM START-UP AND SHUT-DOWN PROCEDURES

To start the system:

1. Fill the boiler to at least six inches above the upper level of the heaters.
2. Energize the air ejector for ten minutes.
3. Circulate water through the cooling water sump by opening the inlet valve and activating the siphon.
4. Energize the power to the boiler and adjust the rheostat until the voltmeter reads 90 V for vacuum operation, or 170 V for atmospheric pressures.
5. Energize the circulating pumps and adjust the throttle for the desired flow through the tube.
6. Open the valve to the auxiliary condenser and adjust the flow: about 15% for vacuum operation or 30% for atmospheric runs.
7. Observe the steam temperature indicated on th efront of the data acquisition unit until the voltage is reached corresponding to the saturation temperature of the the desired operating pressure.
8. Energize the air ejector for two minutes.
9. Adjust the the flow rate through the auxiliary condenser to bring the apparatus to the desired operating pressure.

To secure the system:

1. Secure cooling water to the test tube.
2. Secure power to the boiler.
3. Open the vent valve.
4. Secure the water supply to the auxiliary condenser.

APPENDIX E

COMPUTER PROGRAM LISTINGS

The following pages contain the computer program listings used for this thesis:

PROGRAM SIEDER

```
1000! FILE NAME:    SIEDER
1010! DISK NUMBER: 12
1020! REVISED:      November 29, 1983
1030!
1040  COM /Cc/ C(7)
1050  DIM Emf(10),Tw(5)
1060  DATA 0.10086091,25727.94369,-767345.8295,78025595.81
1070  DATA -9247486589,6.97688E11,-2.66192E13,3.94078E14
1080  READ C(*)
1090  Kcu=385
1100  Di=.0127
1110  Do=.01905
1120  Dr=.015875
1130  L=.13335
1140  L1=.060325
1150  L2=.034925
1160  PRINTER IS 701
1170  BEEP
1180  CLEAR 709
1190  INPUT "ENTER MONTH, DATE AND TIME (MM:DD:HH:MM:SS)",B$
1200  OUTPUT 709;"TD";B$
1210 Series:!
1220  OUTPUT 709;"TD"
1230  ENTER 709;A$
1240  PRINT USING "10X,""Month, date and time: "",14A";A$
1250  BEEP
1260  INPUT "ENTER DISK NUMBER",Dn
1270  PRINT
1280  PRINT USING "10X,""NOTE: Program name: SIEDER"""
1290  PRINT USING "16X,""Disk number  = "",DD";Dn
1300  BEEP
1310  INPUT "ENTER INPUT MODE (1=3054A,2=FILE)",Im
1320  IF Im=1 THEN
1330  BEEP
1340  INPUT "GIVE A NAME FOR THE DATA FILE",D_file$
1350  CREATE BDAT D_file$,10
1360  ELSE
1370  BEEP
1380  INPUT "GIVE THE NAME OF THE DATA FILE",D_file$
1390  BEEP
1400  INPUT "ENTER THE NUMBER OF RUNS STORED",Nrun
1410  PRINT USING "16X,""This analysis was performed for file "",10A";D_file$
1420  END IF
1430  BEEP
1440  INPUT "GIVE A NAME FOR PLOT DATA FILE",Plot$
1450  BEEP
1460  INPUT "ENTER OPTION FOR END-FIN EFFECT (1=Y,0=N)",Ife
1470  IF Ife=0 THEN PRINT USING "16X,""This analysis neglects end-fin effect"""
1480  IF Ife=1 THEN PRINT USING "16X,""This analysis includes end-fin effect"""
1490  CREATE BDAT Plot$,5
1500  ASSIGN @File TO D_file$
1510  ASSIGN @Filep TO Plot$
1520  J=0
1530  Sx=0
1540  Sy=0
1550  Sxs=0
1560  Sxy=0
1570  IF Im=1 THEN
1580! READ DATA THROUGH THE DATA ACQUISITION SYSTEM
```

```
1590! IF THE INPUT MODE (Im) = 1
1600  BEEP
1610  INPUT "ENTER FLOWMETER READING",Fm
1620  OUTPUT 709;"AR AF20 AL30 VR1"
1630  FOR I=0 TO 10
1640  OUTPUT 709;"AS SA"
1650  IF I>4 THEN
1660  Se=0
1670  FOR K=0 TO 19
1680  ENTER 709;E
1690  Se=Se+E
1700  NEXT K
1710  Emf(I)=ABS(Se/20)
1720  ELSE
1730  ENTER 709;E
1740  Emf(I)=ABS(E)
1750  END IF
1760  NEXT I
1770  OUTPUT 713;"T1R2E"
1780  WAIT 2
1790  ENTER 713;T11
1800  OUTPUT 713;"T2R2E"
1810  WAIT 2
1820  ENTER 713;T2
1830  OUTPUT 713;"T1R2E"
1840  WAIT 2
1850  ENTER 713;T12
1860  T1=(T11+T12)*.5
1870  ELSE
1880! READ DATA FROM A USER-SPECIFIED FILE IF
1890! INPUT MODE (Im) = 2
1900  ENTER @File;Emf(*),T1,T2,Fm
1910  END IF
1920  Tavg=(T1+T2)*.5
1930  Twall=0
1940  FOR I=5 TO 10
1950  Tw(I-5)=FNTvsv(Emf(I))
1970  Twall=Twall+Tw(I-5)
1980  NEXT I
1990  Twall=Twall/6
2000  Cpw=FNCpw(Tavg)
2010  Rhow=FNRhow(Tavg)
2020  Md=5.00049E-3+6.9861937E-3*Fm
2030  Md=Md*(1.0365-1.96644E-3*T1+5.252E-6*T1^2)/.995434
2040  Mf=Md/Rhow
2050  Vw=Mf/(PI*Di^2/4)
2051  T2c=T2-(.0138+.001*Vw^2)
2060! T2c=T2-.004*Vw^2
2070  Q=Md*Cpw*(T2c-T1)
2080  Dtw=Q*LOG(Do/Di)/(2*PI*Kcu*L)*.5
2090  Twall=Twall-Dtw
2100  Lmtd=(T2c-T1)/LOG((Twall-T1)/(Twall-T2c))
2110  Kw=FNKw(Tavg)
2120  P1=PI*(Di+Do)
2130  P2=PI*(Di+Dr)
2140  A1=(Do-Di)*PI*Do
2150  A2=(Dr-Di)*PI*Dr
2160  Hi=Q/(PI*Di*L*Lmtd)
2170  IF Ife=0 THEN
2180  Hic=Hi
2190  GOTO 2300
```

```
2200  END IF
2210  M1=(Hi*P1/(Kcu*A1))^.5
2220  M2=(Hi*P2/(Kcu*A2))^.5
2230  Fe1=FNTanh(M1*L1)/(M1*L1)
2240  Fe2=FNTanh(M2*L2)/(M2*L2)
2250  Hic=Q/(PI*Di*(L+L1*Fe1+L2*Fe2)*Lmtd)
2260  IF ABS((Hi-Hic)/Hic)>.01 THEN
2270  Hi=(Hic+Hi)*.5
2280  GOTO 2210
2290  END IF
2300  PRINT
2310  PRINT USING "10X,""Position number           :    1      2      3      4      5
   6"""
2320  PRINT USING "10X,""Wall temperature (Deg C) : "",6(DD.DD,1X)";Tw(*)
2330! CALCULATE THE NUSSELT NUMBER
2340  Nu=Hic*Di/Kw
2350  Muw=FNMuw(Tavg)
2360  Re=Rhow*Vw*Di/Muw
2370  Cf=(Muw/FNMuw(Twall))^.14
2380  Prw=FNPrw(Tavg)
2390  X=Re^.8*Prw^.3333*Cf
2400! COMPUTE COEFFICIENTS FOR THE LEAST-SQUARES-FIT
2410! STRAIGHT LINE
2420  OUTPUT @Filep;X,Nu
2430  PRINT USING "10X,""Twall   Tin    Tout   Lmtd   Vw      X          Nu"""
2440  PRINT USING "10X,4(2D.2D,2X),Z.DD,2X,5D.D,2X,4D.D";Twall,T1,T2c,Lmtd,Vw,X,
Nu
2450  Sx=Sx+X
2460  Sy=Sy+Nu
2470  Sxs=Sxs+X*X
2480  Sxy=Sxy+X*Nu
2490! STORE RAW DATA IN A USER-SPECIFIED FILE IF
2500! INPUT MODE (Im) = 1
2510  IF Im=1 THEN OUTPUT @File;Emf(*),T1,T2,Fm
2520  BEEP
2530  J=J+1
2540  IF Im=1 THEN
2550  INPUT "ARE YOU TAKING MORE DATA (1=YES,0=NO)?",Go_on
2560  Nrun=J
2570  IF Go_on=1 THEN 1570
2580  ELSE
2590  IF J<Nrun THEN 1570
2600  END IF
2610! Ci=Sxy/Sxs
2620  Ci=(Nrun*Sxy-Sy*Sx)/(Nrun*Sxs-Sx^2)
2630  Ac=(Sy-Ci*Sx)/Nrun
2640  PRINT
2650  PRINT USING "10X,""Sieder-Tate Coefficient  = "",D.4D";Ci
2660  PRINT
2670  PRINT USING "10X,""Least-Squares Line:"""
2680  PRINT USING "12X,""Slope          = "",MD.5DE,";Ci
2690  PRINT USING "12X,""Intercept      = "",MD.5DE,";Ac
2691  PRINT
2700  IF Im=1 THEN
2720  BEEP
2730  PRINT USING "10X,""NOTE: "",ZZ,"" data runs were stored in file "",8A";Nru
n,D_file$
2731  ELSE
2732  PRINT USING "10X,""NOTE: The above analysis was performed for file "",14A"
;D_file$
```

```
2740 END IF
2750 PRINT USING "16X,""Plot data are stored in file "",14A";Plot$
2760 ASSIGN @File TO *
2770 ASSIGN @Filep TO *
2780 END
2790 DEF FNRhow(T)
2800 Ro=1006.35724-T*(.774489-T*(2.262459E-2-T*3.03304E-4))
2810 RETURN Ro
2820 FNEND
2830 DEF FNPrw(T)
2840 Prw=FNCpw(T)*FNMuw(T)/FNKw(T)
2850 RETURN Prw
2860 FNEND
2870 DEF FNMuw(T)
2880 A=247.8/(T+133.15)
2890 Muw=2.4E-5*10^A
2900 RETURN Muw
2910 FNEND
2920 DEF FNKw(T)
2930 Kw=.572183504477+1.52770121209E-3*T
2940 RETURN Kw
2950 FNEND
2960 DEF FNTvsv(Emf)
2970 COM /Cc/ C(7)
2980 Sum=C(0)
2990 FOR I=1 TO 7
3000 Sum=Sum+C(I)*Emf^I
3010 NEXT I
3020 RETURN Sum
3030 FNEND
3040 DEF FNCpw(T)
3050 Cpw=(4.21120858-T*(2.26826E-3-T*(4.42361E-5+T*2.71428E-7)))*1000
3060 RETURN Cpw
3070 FNEND
3080 DEF FNTanh(X)
3090 P=EXP(X)
3100 Q=EXP(-X)
3110 Tanh=(P+Q)/(P-Q)
3120 RETURN Tanh
3130 FNEND
```

PROGRAM WILSON

```
1000! FILE NAME: WILSON
1010! REVISED:   December 5. 1983
1020!
1030  COM /Cc/ C(7)
1040  DATA 0.10086091.25727.94369.-767345.8295.78025595.81
1050  DATA -9247486589.6.97688E11,-2.66192E13.3.94078E14
1060  READ C(*)
1070  DIM Emf(4)
1080  L=.130175
1090  L1=.060325
1100  L2=.034925
1110  Do=.01905
1120  Di=.0127
1130  Dr=.015785
1140  Kcu=385
1150  Rm=Do*LOG(Do/Di)/(2*Kcu)
1160  PRINTER IS 701
1170  BEEP
1180  CLEAR 709
1190  INPUT "ENTER MONTH. DATE, AND TIME (MM:DD:HH:MM:SS",B$
1200  OUTPUT 709;"TD";B$
1210  Jp=0
1220  OUTPUT 709;"TD"
1230  ENTER 709:A$
1240  PRINT USING "10X,""Month, date and time  : "",14A":A$
1250  BEEP
1260  INPUT "ENTER DISK NUMBER",Dn
1270  PRINT
1280  PRINT USING "10X,""NOTE: Program name  : M_WILSON"""
1290  PRINT USING "16X,""Disk number    = "",DD";Dn
1300  BEEP
1310  INPUT "ENTER INPUT MODE (1=3054A,2=FILE)",Im
1320  IF Im=1 THEN
1330  BEEP
1340  INPUT "GIVE A NAME FOR THE DATA FILE",D_file$
1350  CREATE BDAT D_file$,10
1360  ELSE
1370  BEEP
1380  INPUT "GIVE THE NAME OF THE DATA FILE",D_file$
1390  PRINT USING "16X,""This analysis is for data in file "",14A":D_file$
1400  BEEP
1410  INPUT "ENTER THE NUMBER OF RUNS STORED",Nrun
1420  END IF
1430  BEEP
1440  INPUT "GIVE A NAME FOR PLOT-DATA FILE",Plot$
1450  BEEP
1460  INPUT "ENTER OPTION (1=QCT,2=T-PILE,3=AVE)",Itm
1470  BEEP
1480  INPUT "ENTER OPTION FOR END-FIN EFFECT (1=Y,0=N)",Ife
1490  IF Itm=1 THEN PRINT USING "16X,""This analysis uses QCT readings"""
1500  IF Itm=2 THEN PRINT USING "16X,""This analysis uses T-PILE readings"""
1510  IF Itm=3 THEN PRINT USING "16X,""This analysis uses average of QCT and T-P
ILE readings"""
1520  IF Ife=1 THEN PRINT USING "16X,""This analysis includes end-fin effect"""
1530  IF Ife=0 THEN PRINT USING "16X,""This analysis neglects end-fin effect"""
1540  CREATE BDAT Plot$,10
1550  ASSIGN @Filep TO Plot$
1560! Ciu=.040
1570! Cil=.028
```

```
1580  Jj=0
1590  Ci=.03
1600  J=0
1610! Ci=(Ciu+Cil)*.5
1620  Sx=0
1630  Sy=0
1640  Sxs=0
1650  Sxy=0
1660  PRINT
1670  PRINT USING "10X,""Iteration number                    = "",DD";Jj+1
1680  IF Jj=0 OR Jp=1 THEN
1690  PRINT
1700  PRINT USING "12X,""T1        T2     Tsat     Lmtd      √w       X         Y"""""
1710  END IF
1720  ASSIGN @File TO D_file$
1730  IF Im=1 AND Jj=0 THEN
1740! READ DATA THROUGH THE DATA ACQUISITION SYSTEM
1750! IF THE INPUT MODE (Im) = 1
1760  BEEP
1770  INPUT "ENTER FLOWMETER READING",Fm
1780  OUTPUT 709;"AR AF60 AL63"
1790  OUTPUT 709;"AS SA"
1800  Etp=0
1810  FOR I=1 TO 20
1820  ENTER 709:Et
1830  Etp=Etp+Et
1840  NEXT I
1850  Etp=Etp/20
1860  OUTPUT 709;"AS SA"
1870  Ptran=0
1880  FOR I=1 TO 50
1890  ENTER 709;Pt
1900  Ptran=Ptran+Pt
1910  NEXT I
1920  Ptran=Ptran/50
1930  OUTPUT 709;"AS SA"
1940  ENTER 709:Bvol
1950  OUTPUT 709;"AS SA"
1960  ENTER 709:Bamp
1970  OUTPUT 709;"AR AF20 AL24"
1980  FOR I=0 TO 4
1990  OUTPUT 709;"AS SA"
2000  ENTER 709:Emf(I)
2010  Emf(I)=ABS(Emf(I))
2020  NEXT I
2030  OUTPUT 713;"T1R2E"
2040  WAIT 2
2050  ENTER 713;T11
2060  OUTPUT 713;"T2R2E"
2070  WAIT 2
2080  ENTER 713;T2
2090  OUTPUT 713;"T1R2E"
2100  WAIT 2
2110  ENTER 713;T12
2120  T1=(T11+T12)*.5
2130  CLEAR 713
2140  ELSE
2150! READ DATA FROM A USER-SPECIFIED FILE IF INPUT MODE (Im) = 2
2160  ENTER @File;Bvol,Bamp,Ptran,Etp,Emf(*),Fm,T1,T2
2170  END IF
2180  Tsat=FNTvsv((Emf(0)+Emf(1))*.5)
```

```
2190  Ti=FNTvsv(Emf(2))
2200  Grad=FNGrad((T1+T2)*.5)
2210  To=Ti+ABS(Etp)/(10*Grad)*1.E+6
2220  IF Jj=0 THEN
2230  Er1=ABS(Ti-T1)
2240  PRINTER IS 1
2250  PRINT USING """T1            = "",DD.3D":T1
2260  PRINT USING """Ti            = "",DD.DD":Ti
2270  IF Er1>.5 THEN
2280  BEEP
2290  PRINT "QCT AND TC DIFFER MORE THAN 0.5 C"
2300  BEEP
2310  INPUT "OK TO GO AHEAD (1=Y,0=N)?",Ok1
2320  END IF
2330  PRINT USING """DT (QCT)      = "",Z.3D":T2-T1
2340  PRINT USING """DT (T-PILE) = "",Z.3D":To-Ti
2350  IF Ok1=0 AND Er1>.5 THEN 3600
2360  Er2=ABS((T2-T1)-(To-Ti))/(T2-T1)
2370  IF Er2>.05 THEN
2380  BEEP
2390  PRINT "QCT AND T-PILE DIFFER MORE THAN 5%"
2400  BEEP
2410  INPUT "OK TO GO AHEAD (1=Y,0=N)?",Ok2
2420  IF Ok2=0 AND Er2>.05 THEN 3600
2430  END IF
2440  PRINTER IS 701
2450  END IF
2460! CALCULATE THE LOG-MEAN-TEMPERATURE DIFFERENCE
2470  IF Itm=1 THEN
2480  Tf=T1
2490  Tl=T2
2500  END IF
2510  IF Itm=2 THEN
2520  Tf=Ti
2530  Tl=To
2540  END IF
2550  IF Itm=3 THEN
2560  Tf=(T1+Ti)*.5
2570  Tl=(T2+To)*.5
2580  END IF
2590  Tavg=(Tf+Tl)*.5
2600  Trise=Tl-Tf
2610  Lmtd=Trise/LOG((Tsat-Tf)/(Tsat-Tl))
2620  Cpw=FNCpw(Tavg)
2630  Rhow=FNRhow(Tavg)
2640  Kw=FNKw(Tavg)
2650  Muwa=FNMuw(Tavg)
2660  Prw=FNPrw(Tavg)
2670  Mdt=5.00049E-3+6.9861937E-3*Fm
2680  Md=Mdt*(1.0365-Tf*(1.96644E-3-Tf*5.252E-6))/.995434
2690  Vf=Md/Rhow
2700  Vw=Vf/(PI*Di^2/4)
2710  Trise=Trise-.004*Vw^2
2720  Q=Md*Cpw*Trise
2730  Qp=Q/(PI*Do*L)
2740  Uo=Qp/Lmtd
2750  Re=Rhow*Vw*Di/Muwa
2760  Fe1=0
2770  Fe2=0
2780  Cf=1
2790  Two=Tsat-5
```

```
2800  Tfilm=Tsat/2+Two/2
2810  Kf=FNKw(Tfilm)
2820  Rhof=FNRhow(Tfilm)
2830  Muf=FNMuw(Tfilm)
2840  Hfgp=FNHfg(Tsat)+.68*FNCpw(Tfilm)*(Tsat-Two)
2850  New=Kf*(Rhof^2*9.799*Hfgp/(Muf*Do*Qp))^.3333
2860  Ho=.655*New
2870  Twoc=Tsat-Qp/Ho
2880  IF ABS((Twoc-Two)/Twoc)>.001 THEN
2890  Two=Twoc
2900  GOTO 2800
2910  END IF
2920  Cf=1.0
2930  Omega=Re^.8*Prw^.3333*Cf
2940  Hi=Kw/Di*Ci*Omega
2950  IF Ife=0 THEN 3040
2960  P1=PI*(Di+Do)
2970  P2=PI*(Di+Dr)
2980  A1=(Do-Di)*PI*(Di+Do)*.5
2990  A2=(Dr-Di)*PI*(Di+Dr)*.5
3000  M1=(Hi*P1/(Kcu*A1))^.5
3010  M2=(Hi*P2/(Kcu*A2))^.5
3020  Fe1=FNTanh(M1*L1)/(M1*L1)
3030  Fe2=FNTanh(M2*L2)/(M2*L2)
3040  Dt=Q/(PI*Di*(L+L1*Fe1+L2*Fe2)*Hi)
3050  Cfc=(Muwa/FNMuw(Tavg+Dt))^.14
3060  IF ABS((Cfc-Cf)/Cfc)>.01 THEN
3070  Cf=(Cf+Cfc)*.5
3080  GOTO 2930
3090  END IF
3100  X=Do*New/(Omega*Kw)
3110  Y=New*(1/Uo-Rm)
3120! COMPUTE COEFFICIENTS FOR THE LEAST-SQUARES-FIT STRAIGHT LINE
3130  IF Jp=1 THEN OUTPUT @Filep;X,Y
3140  Sx=Sx+X
3150  Sy=Sy+Y
3160  Sxs=Sxs+X*X
3170  Sxy=Sxy+X*Y
3180! STORE RAW DATA IN A USER-SPECIFIED FILE IF INPUT MODE (Im) = 1
3190  IF Im=1 AND Jj=0 THEN OUTPUT @File;Bvol,Bamp,Ptran,Etp,Emf(*),Fm,T1,T2
3200  IF Jj=0 OR Jp=1 THEN PRINT USING "8X,5(2X,3D.DD),2(2X,D.5D)";Tf,Tl,Tsat,Lm
td,Vw,X,Y
3210  BEEP
3220  J=J+1
3230  IF Im=1 AND Jj=0 THEN
3240  INPUT "DO YOU HAVE MORE DATA (1=Y,0=N)?",Go_on
3250  Nrun=J
3260  IF Go_on=1 THEN 1730
3270  ELSE
3280  IF J<Nrun THEN 1730
3290  END IF
3300  Sl=(Nrun*Sxy-Sy*Sx)/(Nrun*Sxs-Sx^2)
3310  Ac=(Sy-Sl*Sx)/Nrun
3320  Cic=1/Sl
3330  Jj=Jj+1
3340  IF Jp=1 THEN Jp=2
3350  IF ABS((Cic-Ci)/Cic)>.001 THEN
3360  Ci=(Cic+Ci)*.5
3370  PRINT USING "10X,""Intermediate Sieder-Tate coefft = "",Z.4D";Ci
3380  GOTO 1600
```

```
3390  ELSE
3400  IF Jp=0 THEN Jp=1
3410  END IF
3420  IF Jp=1 THEN 1600
3430  Ci=(Ci+Cic)*.5
3440  PRINT
3450  PRINT USING "10X,""Sieder-Tate coefficient          = "",Z.4D";Ci
3460  PRINT
3470  PRINT USING "10X,""Least-Squares Line:"""
3480  PRINT USING "10X,""  Slope      =  "",Z.5DE,";Sl
3490  PRINT USING "10X,""  Intercept = "",MZ.5DE,";Ac
3500  PRINT
3510  IF Im=1 THEN
3520  BEEP
3530  PRINT USING "10X,""NOTE: "",ZZ,"" data runs are stored in file "",8A";J,D_
file$
3540  ELSE
3550  PRINT USING "10X,""NOTE: Above analysis was performed for data in file "",
10A";D_file$
3560  END IF
3570  PRINT USING "16X,""Plot data are stored in file "",10A";Plot$
3580  ASSIGN @File TO *
3590  ASSIGN @Filep TO *
3600  END
3610  DEF FNRhow(T)
3620  Ro=1006.35724-T*(.774489-T*(2.262459E-2-T*3.03304E-4))
3630  RETURN Ro
3640  FNEND
3650  DEF FNPrw(T)
3660  Prw=FNCpw(T)*FNMuw(T)/FNKw(T)
3670  RETURN Prw
3680  FNEND
3690  DEF FNMuw(T)
3700  A=247.8/(T+133.15)
3710  Mu=2.4E-5*10^A
3720  RETURN Mu
3730  FNEND
3740  DEF FNKw(T)
3750  X=(T+273.15)/273.15
3760  Kw=-.92247+X*(2.8395-X*(1.8007-X*(.52577-.07344*X)))
3770  RETURN Kw
3780  FNEND
3790  DEF FNTvsv(Emf)
3800  COM /Cc/ C(7)
3810  Sum=C(0)
3820  FOR I=1 TO 7
3830  Sum=Sum+C(I)*Emf^I
3840  NEXT I
3850  RETURN Sum
3860  FNEND
3870  DEF FNCpw(T)
3880  Cpw=(4.21120858-T*(2.26826E-3-T*(4.42361E-5+2.71428E-7)))*1000
3890  RETURN Cpw
3900  FNEND
3910  DEF FNTanh(X)
3920  P=EXP(X)
3930  Q=EXP(-X)
3940  Tanh=(P+Q)/(P-Q)
3950  RETURN Tanh
3960  FNEND
3970  DEF FNGrad(T)
```

```
3980  COM /Cc/ C(7)
3990  Grad=37.9853+.104388*T
4000  RETURN Grad
4010  FNEND
4020  DEF FNFvst(T)
4030  F=466.444+T*(7.09451-T*1.65808E-2)
4040  RETURN F
4050  FNEND
4060  DEF FNHfg(T)
4070  Hfg=2477200-2450*(T-10)
4080  RETURN Hfg
4090  FNEND
```

PROGRAM DRP

```
1000! FILE NAME: DRP
1010! REVISED:  November 18. 1983
1020!
1030 COM /Cc/ C(7)
1040 DIM Emf(10)
1050 DATA 0.10086091.25727.94369.-767345.8295.78025595.81
1060 DATA -9247486589.6.97688E+11.-2.66192E+13.3.94078E+14
1070 READ C(*)
1080 Di=.0127       ! Inside diameter of test tube
1090 Do=.01905      ! Outside diameter of test tube
1100 Dr=.015875     ! Outside diameter of the outlet end
1110 Dssp=.1524     ! Inside diameter of stainless steel test section
1120 Ax=PI*Dssp^2/4-PI*Do*L
1130 L=.130175      ! Condensing length
1140 L1=.060325     ! Inlet end "fin length"
1150 L2=.034925     ! Outlet end "fin length"
1160 Kcu=385        ! Thermal conductivity of Copper
1170 Ci=.034        ! Sieder-Tate coefficient
1180 Rm=Do*LOG(Do/Di)/(2*Kcu) ! Wall resistance based on outside area
1190 PRINTER IS 701
1200 CLEAR 709
1210 BEEP
1220 INPUT "ENTER MONTH, DATE AND TIME (MM:DD:HH:MM:SS)",Date$
1230 OUTPUT 709:"TD";Date$
1240 OUTPUT 709:"TD"
1250 ENTER 709:Date$
1260 PRINT "              Month, date and time :";Date$
1270 PRINT
1280 PRINT USING "10X,""NOTE: Program name : DRP"""
1290 BEEP
1300 INPUT "ENTER DISK NUMBER",Dn
1310 PRINT USING "16X,""Disk number  = "",DD";Dn
1320 BEEP
1330 INPUT "ENTER INPUT MODE (1=3054A,2=FILE)",Im
1340 IF Im=1 THEN
1350 BEEP
1360 INPUT "GIVE A NAME FOR THE RAW DATA FILE",D_file$
1370 CREATE BDAT D_file$,15
1380 ASSIGN @File TO D_file$
1390 BEEP
1400 INPUT "ENTER GEOMETRY CODE (1=FINNED,0=PLAIN)",Ifg
1410 OUTPUT @File:Ifg
1420 IF Ifg=0 THEN
1430 BEEP
1440 INPUT "WALL TEMPERATURE MEASUREMENT (1=Y,0=N)",Iwt
1450 ELSE
1460 BEEP
1470 INPUT "ENTER FIN PITCH, WIDTH AND HEIGHT",Fp,Fw,Fh
1480 END IF
1490 IF Ifg=0 THEN OUTPUT @File:Iwt
1500 IF Ifg=1 THEN OUTPUT @File:Fp,Fw,Fh
1510 ELSE
1520 BEEP
1530 INPUT "GIVE THE NAME OF THE EXISTING DATA FILE",D_file$
1540 PRINT USING "16X,""This analysis was performed for data in file "",10A";D_
```

```
files
1550  BEEP
1560  INPUT "ENTER THE NUMBER OF RUNS STORED",Nrun
1570  ASSIGN @File TO D_files
1580  ENTER @File:Ifg
1590  IF Ifg=0 THEN ENTER @File:Iwt
1600  IF Ifg=1 THEN ENTER @File:Fp,Fw,Fh
1610  END IF
1620  IF Ifg=0 THEN
1630  BEEP
1640  INPUT "WANT TO CREATE A FILE FOR Nr vs F (1=Y,0=N)?",Inf
1650  ELSE
1660  Inf=0
1670  END IF
1680  IF Inf=1 THEN
1690  BEEP
1700  INPUT "GIVE A NAME FOR Nr vs F FILE",Nrf$
1710  CREATE BDAT Nrf$,2
1720  ASSIGN @Nrf TO Nrf$
1730  END IF
1740  BEEP
1750  INPUT "ENTER OPTION (1=QCT,2=T-PILE,3=AVE)",Itm
1760  BEEP
1770  INPUT "ENTER OPTION FOR END-FIN EFFECT (1=Y,0=N)",Ife
1780  IF Itm=1 THEN PRINT USING "16X,""This analysis uses QCT readings"""
1790  IF Itm=2 THEN PRINT USING "16X,""This analysis uses T-PILE readings"""
1800  IF Itm=3 THEN PRINT USING "16X,""This analysis uses average of QCT and T-P
ILE readings"""
1810  IF Ife=1 THEN PRINT USING "16X,""This analysis includes end-fin effect"""
1820  IF Ife=0 THEN PRINT USING "16X,""This analysis neglects end-fin effect"""
1830  PRINT USING "16X,""Sieder-Tate coefficient   = "",Z.4D":Ci
1840  BEEP
1850  INPUT "GIVE A NAME FOR PLOT DATA FILE",P_file$
1860  CREATE BDAT P_file$,5
1870  ASSIGN @Filep TO P_file$
1880  IF Iwt=1 THEN
1890  BEEP
1900  INPUT "GIVE A NAME FOR WALL TEMPERATURE FILE",Wtf$
1910  CREATE BDAT Wtf$,5
1920  ASSIGN @File1 TO Wtf$
1930  END IF
1940  BEEP
1950  INPUT "ENTER OUTPUT VERSION (1=SHORT,2=LONG)",Iov
1960! IF Im=1 THEN
1970! OUTPUT @File:Ifg
1980! IF Ifg=0 THEN OUTPUT @File:Iwt
1990! IF Ifg=1 THEN OUTPUT @File:Fp,Fw,Fh
2000! ELSE
2010! ENTER @File:Ifg
2020! IF Ifg=0 THEN ENTER @File:Iwt
2030! IF Ifg=1 THEN ENTER @File:Fp,Fw,Fh
2040! END IF
2050  IF Ifg=0 THEN
2060  PRINT USING "16X,""Tube type    : PLAIN"""
2070  ELSE
2080  PRINT USING "16X,""Tube type    : FINNED"""
2090  PRINT USING "16X,""Fin pitch, width, and height (mm): "",DD.D,2X,Z.DD,2X,Z
.DD":Fp,Fw,Fh
2100  END IF
2110  J=0
2120  IF Iov=1 THEN
```

```
2130  PRINT
2140  IF Inf=1 THEN
2150  PRINT USING "10X,""Data  Vw       Uo        Ho         Qp       Vv     F      Nr
"""""
2160  PRINT USING "10X,"" #   (m/s) (W/m`2-K)(W/m`2-K)  (W/m`2) (m/s)"""""
2170  ELSE
2180  PRINT USING "10X,""Data  Vw          Uo           Ho            Qp          Vv"""""
2190  PRINT USING "10X,"" #   (m/s)    (W/m`2-K)    (W/m`2-K)    (W/m 2)    (m/s)""
"
2200  END IF
2210  END IF
2220  Sx=0
2230  Sy=0
2240  Sxs=0
2250  Sxy=0
2260 Repeat:!
2270  J=J+1
2280  IF Im=1 THEN
2290  BEEP
2300  INPUT "LIKE TO CHECK NG CONCENTRATION (1=Y,0=N)?",Ng
2310  BEEP
2320  INPUT "ENTER FLOWMETER READING",Fm
2330  OUTPUT 709:"AR AF60 AL63 VR5"
2340  OUTPUT 709:"AS SA"
2350  ENTER 709;Etp
2360  OUTPUT 709:"AS SA"
2370  Vtran=0
2380  FOR I=1 TO 50
2390  ENTER 709;Vt
2400  Vtran=Vtran+Vt
2410  NEXT I
2420  Vtran=Vtran/50
2430  OUTPUT 709;"AS SA"
2440  ENTER 709;Bvol
2450  OUTPUT 709;"AS SA"
2460  ENTER 709;Bamp
2470  IF Iwt=0 THEN OUTPUT 709;"AR AF20 AL24 VR1"
2480  IF Iwt=1 THEN OUTPUT 709;"AR AF20 AL30 VR1"
2490  IF Iwt=0 THEN Nn=4
2500  IF Iwt=1 THEN Nn=10
2510  FOR I=0 TO Nn
2520  OUTPUT 709;"AS SA"
2530  IF I>4 THEN
2540  Se=0
2550  FOR K=0 TO 10
2560  ENTER 709;E
2570  Se=Se+E
2580  NEXT K
2590  Emf(I)=ABS(Se/10)
2600  ELSE
2610  ENTER 709;E
2620  Emf(I)=ABS(E)
2630  END IF
2640  NEXT I
2650  OUTPUT 713;"T1R2E"
2660  WAIT 2
2670  ENTER 713;T11
2680  OUTPUT 713;"T2R2E"
2690  WAIT 2
2700  ENTER 713;T2
```

```
2710 OUTPUT 713;"T1R2E"
2720 WAIT 2
2730 ENTER 713;T12
2740 T1=(T11+T12)*.5
2750 IF Ng=0 THEN 2800
2760 BEEP
2770 INPUT "ENTER MANOMETER READING (HL,HR.HRW)",Hl,Hr,Hrw
2780 Phg=Hl+Hr
2790 Pwater=Hr-Hrw
2800 ELSE
2810 IF Ifg=1 OR Iwt=0 THEN
2820 ENTER @File;Bvol,Bamp,Vtran,Etp,Emf(0),Emf(1),Emf(2),Emf(3),Emf(4),Fm,T1,T
2,Phg,Pwater
2830 END IF
2840 IF Ifg=0 AND Iwt=1 THEN ENTER @File:Bvol,Bamp,Vtran,Etp,Emf(*),Fm,T1,T2,Ph
g,Pwater
2850 IF J=1 OR J=10 OR J=20 OR J=Nrun THEN
2860 Ng=1
2870 ELSE
2880 Ng=0
2890 END IF
2900 END IF
2910 Tsteam=FNTvsv((Emf(0)+Emf(1))*.5)  ! COMPUTE STEAM TEMPERATURE
2920 Troom=FNTvsv(Emf(3))
2930 IF Iwt=1 THEN
2940 Twm=0.
2950 FOR I=0 TO 5
2960 Tw(I)=FNTvsv(Emf(I+5))
2970 Twm=Twm+Tw(I)
2980 NEXT I
2990 Twm=Twm/6
3000 END IF
3010 Tcon=FNTvsv(Emf(4))
3020 Psat=FNPvst(Tsteam)
3030 Rohg=13529-122*(Troom-26.85)/50
3040 Rowater=FNRhow(Troom)
3050 Ptest=(Phg*Rohg-Pwater*Rowater)*9.799/1000
3060 Pmm=Ptest/133.322
3070 Pkm=Ptest*1.E-3
3080 Pks=Psat*1.E-3
3090 Pkt=FNPvsv(Vtran)*1.E-3
3100 Tsat=FNTvsp(Ptest)
3110 Vst=FNVvst(Tsteam)
3120 Ppng=(Ptest-Psat)/Ptest
3130 Ppst=1-Ppng
3140 Mfng=1/(1+18.015/28.97*Psat/(Ptest-Psat))
3150 Vfng=Mfng/(1.608-.608*Mfng)
3160 Mfng=Mfng*100
3170 Vfng=Vfng*100
3180 BEEP
3190 IF Iov=2 THEN
3200 PRINT
3210 PRINT USING "10X,""Data set number            = "",DD";J
3220 PRINT
3230 END IF
3240 IF Iov=2 AND Ng=1 THEN
3250 PRINT USING "10X,""         P          Psat    Ptran    Tmeas    Tsat         N
G %"""""
3260 PRINT USING "10X,"" (mm)    (kPa)    (kPa)    (kPa)     (C)      (C)     Molal
    Mass"""""
3270 PRINT USING "10X,5(3D.DD,2X),2(3D.DD,2X),2(M3D.D,2X)";Pmm,Pkm,Pks,Pkt,Tste
```

```
am,Tsat,Vfng,Mfng
3280  PRINT
3290  END IF
3300  IF Mfng>.5 THEN
3310  BEEP
3320  PRINT
3330  IF Im=1 THEN
3340  BEEP
3350  PRINT
3360  PRINT USING "10X,""Energize the vacuum system """
3370  BEEP
3380  INPUT "OK TO ACCEPT THIS RUN (1=Y,0=N)?",Ok
3390  IF Ok=0 THEN
3400  BEEP
3410  DISP "NOTE: THIS DATA SET WILL BE DISCARDED!! "
3420  WAIT 5
3430  GOTO 2280
3440  END IF
3450  END IF
3460  END IF
3470  IF Im=1 THEN
3480  IF Ifg=1 OR Iwt=0 THEN
3490  OUTPUT @File;Bvol,Bamp,Vtran,Etp,Emf(0),Emf(1),Emf(2),Emf(3),Emf(4),Fm,T1,
T2,Phg,Pwater
3500  END IF
3510  IF Ifg=0 AND Iwt=1 THEN OUTPUT @File;Bvol,Bamp,Vtran,Etp,Emf(*),Fm,T1,T2,P
hg,Pwater
3520  END IF
3530  IF Ifg=0 AND Iwt=1 THEN OUTPUT @File1;Tw(*)
3540! ANALYSIS BEGINS
3550  Ti=FNTvsv(Emf(2))
3560  Grad=FNGrad((T1+T2)*.5)
3570  To=Ti+ABS(Etp)/(10*Grad)*1.E+6
3580  Er1=ABS(Ti-T1)
3590  PRINTER IS 1
3600  PRINT USING """T1 (QCT)      = "",DD.3D";T1
3610  PRINT USING """Ti (TC)       = "",DD.3D";Ti
3620  IF Er1>.5 THEN
3630  BEEP
3640  PRINT "QCT AND TC DIFFER BY MORE THAN 0.5 C"
3650  BEEP
3660  INPUT "OK TO GO AHEAD (1=Y,0=N)?",Ok1
3670  END IF
3680  PRINT USING """DT (QCT)      = "",Z.3D";T2-T1
3690  PRINT USING """DT (T-PILE) = "",Z.3D";To-Ti
3700  IF Ok1=0 AND Er1>.5 THEN 5100
3710  Er2=ABS((T2-T1)-(To-Ti))/(T2-T1)
3720  IF Er2>.05 THEN
3730  BEEP
3740  PRINT "QCT AND T-PILE DIFFER BY MORE THAN 5%"
3750  BEEP
3760  INPUT "OK TO GO AHEAD (1=Y,0=N)?",Ok2
3770  IF Ok2=0 AND Er2>.05 THEN 5100
3780  END IF
3790  PRINTER IS 701
3800  IF Itm=1 THEN
3810  T1i=T1
3820  T2o=T2
3830  END IF
3840  IF Itm=2 THEN
3850  T1i=Ti
```

```
3860  T2o=To
3870  END IF
3880  IF Itm=3 THEN
3890  T1i=(T1+Ti)*.5
3900  T2o=(T2+To)*.5
3910  END IF
3920  Tavg=(T1i+T2o)*.5
3930  Cpw=FNCpw(Tavg)
3940  Rhow=FNRhow(Tavg)
3950  Md=5.00049E-3+6.9861937E-3*Fm
3960  Md=Md*(1.0365-1.96644E-3*Tavg+5.252E-6*Tavg^2)/.995434
3970  Mf=Md/Rhow
3980  Vw=Mf/(PI*Di^2/4)
3990  T2o=T2o-(.0138+.001*Vw^2)
4000  Q=Md*Cpw*(T2o-T1i)
4010  Qp=Q/(PI*Do*L)
4020  Kw=FNKw(Tavg)
4030  Muw=FNMuw(Tavg)
4040  Rei=Rhow*Vw*Di/Muw
4050  Prw=FNPrw(Tavg)
4060  Fe1=0.
4070  Fe2=0.
4080  Cf=1.
4090  Hi=Kw*Ci/Di*Rei^.8*Prw^.3333*Cf
4100  Dt=Q/(PI*Di*(L+L1*Fe1+L2*Fe2)*Hi)
4110  Cfc=(Muw/FNMuw(Tavg+Dt))^.14
4120  IF ABS((Cfc-Cf)/Cfc)>.01 THEN
4130  Cf=(Cf+Cfc)*.5
4140  GOTO 4090
4150  END IF
4160  IF Ife=0 THEN GOTO 4250
4170  P1=PI*(Di+Do)
4180  A1=(Do-Di)*PI*(Di+Do)*.5
4190  M1=(Hi*P1/(Kcu*A1))^.5
4200  P2=PI*(Di+Dr)
4210  A2=(Dr-Di)*PI*(Di+Dr)*.5
4220  M2=(Hi*P2/(Kcu*A2))^.5
4230  Fe1=FNTanh(M1*L1)/(M1*L1)
4240  Fe2=FNTanh(M2*L2)/(M2*L2)
4250  Lmtd=(T2o-T1i)/LOG((Tsteam-T1i)/(Tsteam-T2o))
4260  Uo=Q/(Lmtd*PI*Do*L)
4270  Ho=1/(1/Uo-Do*L/(Di*(L+L1*Fe1+L2*Fe2)*Hi)-Rm)
4280  Dtc=Q/(PI*Di*(L+L1*Fe1+L2*Fe2)*Hi)
4290  IF ABS((Dtc-Dt)/Dtc)>.01 THEN 4090
4300  Hfg=FNHfg(Tsteam)
4310  Two=Tsteam-Qp/Ho
4320  Tfilm=Tsteam/3+2*Two/3
4330  Kf=FNKw(Tfilm)
4340  Rhof=FNRhow(Tfilm)
4350  Muf=FNMuw(Tfilm)
4360  Hpq=.651*Kf*(Rhof^2*9.81*Hfg/(Muf*Do*Qp))^.3333
4370  Y=Hpq*Qp^.3333
4380  X=Qp
4390  Sx=Sx+X
4400  Sy=Sy+Y
4410  Sxs=Sxs+X^2
4420  Sxy=Sxy+X*Y
4430  OUTPUT @Filep:Qp,Ho
4440  Q1=500  ! TO BE MODIFIED
4450  Qloss=Q1/(100-25)*(Tsteam-Troom)  ! TO BE MODIFIED
4460  Hfc=FNHf(Tcon)
```

```
4470  Hf=FNHf(Tsteam)
4480  Mdv=0
4490! Bp=(Bvol*100)^2/5.76  ! BOILER POWER IN Watts
4500  Bp=(Bvol*100)^2/5.76
4510  Mdvc=((Bp-Qloss)-Mdv*(Hf-Hfc))/Hfg
4520  IF ABS((Mdv-Mdvc)/Mdvc)>.01 THEN
4530  Mdv=(Mdv+Mdvc)*.5
4540  GOTO 4510
4550  END IF
4560  Mdv=(Mdv+Mdvc)*.5
4570  Vg=FNVvst(Tsteam)
4580  Vv=Mdv*Vg/Ax
4590  IF Inf=1 THEN
4600  F=(9.799*Do*Muf*Hfg)/(Vv^2*Kf*(Tsteam-Two))
4610  Nu=Ho*Do/Kf
4620  Ret=Vv*Rhof*Do/Muf
4630  Nr=Nu/Ret^.5
4640  END IF
4650  IF Inf=1 THEN OUTPUT @Nrf;F,Nr
4660  IF Iov=2 THEN
4670  PRINT USING "10X,""  T (Inlet)       Delta-T"""
4680  PRINT USING "10X,"" QCT      TC     QCT  T-PILE"""
4690  PRINT USING "10X,2(DD.DD,2X),2(Z.3D,2X)";T1,Ti,T2-T1,To-Ti
4700  PRINT USING "10X,"" Vw       Rei          Hi          Uo          Ho          q
       Vv"""
4710  PRINT USING "10X,Z.DD,1X,5(MZ.3DE,1X),MZ.DD";Vw,Rei,Hi,Uo,Ho,Qp,Vv
4720  END IF
4730  IF Iov=1 THEN
4740  IF Inf=1 THEN
4750  PRINT USING "11X,DD,2X,Z.DD,2X,2(5D.D,2X),Z.3DE,1X,Z.DD,2(1X,3D.DD)";J,Vw,
Uo,Ho,Qp,Vv,F,Nr
4760  ELSE
4770  PRINT USING "11X,DD,2X,Z.DD,2X,2(MD.4DE,2X),Z.3DE,3X,Z.DD";J,Vw,Uo,Ho,Qp,V
v
4780  END IF
4790  END IF
4800  IF Im=1 THEN
4810  BEEP
4820  INPUT "WILL THERE BE ANOTHER RUN (1=Y,0=N)?",Go_on
4830  Nrun=J
4840  IF Go_on=1 THEN Repeat
4850  ELSE
4860  IF J<Nrun THEN Repeat
4870  END IF
4880  IF Ifg=0 THEN
4890  PRINT
4900  Sl=(Nrun*Sxy-Sy*Sx)/(Nrun*Sxs-Sx^2)
4910  Ac=(Sy-Sl*Sx)/Nrun
4920  PRINT USING "10X,""Least-Squares Line for Hnu vs q curve:"""
4930  PRINT USING "10X,""  Slope      = "",MD.4DE";Sl
4940  PRINT USING "10X,""  Intercept  = "",MD.4DE";Ac
4950  END IF
4960  IF Im=1 THEN
4970  BEEP
4980  PRINT
4990  PRINT USING "10X,""NOTE: "",ZZ,"" data runs were stored in file "",10A";J,
D_file$
5000  END IF
5010  BEEP
5020  PRINT
5030  PRINT USING "10X,""NOTE: "",ZZ,"" X-Y pairs were stored in plot data file
```

```
"",10A":J,P_file$
5040  IF Inf=1 THEN
5050  PRINT USING "16X,ZZ,"" pairs of Nr-F are stored in file "",14A":J,Nrf$
5060  END IF
5070  ASSIGN @File TO *
5080  ASSIGN @File1 TO *
5090  ASSIGN @Filep TO *
5100  END
5110  DEF FNPvst(Tsteam)
5120  DIM K(8)
5130  DATA -7.691234564,-26.08023696,-168.1706546,64.23285504,-118.9646225
5140  DATA 4.16711732,20.9750676,1.E9,6
5150  READ K(*)
5160  T=(Tsteam+273.15)/647.3
5170  Sum=0
5180  FOR N=0 TO 4
5190  Sum=Sum+K(N)*(1-T)^(N+1)
5200  NEXT N
5210  Br=Sum/(T*(1+K(5)*(1-T)+K(6)*(1-T)^2))-(1-T)/(K(7)*(1-T)^2+K(8))
5220  Pr=EXP(Br)
5230  P=22120000*Pr
5240  RETURN P
5250  FNEND
5260  DEF FNHfg(T)
5270  Hfg=2477200-2450*(T-10)
5280  RETURN Hfg
5290  FNEND
5300  DEF FNMuw(T)
5310  A=247.8/(T+133.15)
5320  Mu=2.4E-5*10^A
5330  RETURN Mu
5340  FNEND
5350  DEF FNVvst(Tt)
5360  P=FNPvst(Tt)
5370  T=Tt+273.15
5380  X=1500/T
5390  F1=1/(1+T*1.E-4)
5400  F2=(1-EXP(-X))^2.5*EXP(X)/X^.5
5410  B=.0015*F1-.000942*F2-.0004882*X
5420  K=2*P/(461.52*T)
5430  V=(1+(1+2*B*K)^.5)/K
5440  RETURN V
5450  FNEND
5460  DEF FNCpw(T)
5470  Cpw=4.21120858-T*(2.26826E-3-T*(4.42361E-5+2.71428E-7*T))
5480  RETURN Cpw*1000
5490  FNEND
5500  DEF FNRhow(T)
5510  Ro=999.52946+T*(.01269-T*(5.482513E-3-T*1.234147E-5))
5520  RETURN Ro
5530  FNEND
5540  DEF FNPrw(T)
5550! Prw=10^(1.09976605-T*(1.3749326E-2-T*(3.968875E-5-3.45026E-7*T)))
5560  Prw=FNCpw(T)*FNMuw(T)/FNKw(T)
5570  RETURN Prw
5580  FNEND
5590  DEF FNKw(T)
5600! Kw=.5625894+T*(2.2964546E-3-T*(1.509766E-5-4.0581652E-8*T))
5610  X=(T+273.15)/273.15
5620  Kw=-.92247+X*(2.8395-X*(1.8007-X*(.52577-.07344*X)))
5630  RETURN Kw
```

```
5640  FNEND
5650  DEF FNTanh(X)
5660  P=EXP(X)
5670  Q=EXP(-X)
5680  Tanh=(P+Q)/(P-Q)
5690  RETURN Tanh
5700  FNEND
5710  DEF FNTvsv(V)
5720  COM /Cc/ C(7)
5730  Sum=C(0)
5740  FOR I=1 TO 7
5750  Sum=Sum+C(I)*V^I
5760  NEXT I
5770! T=V*(.02635206856-V*(9.7351313E-7-V*6.576805E-11))
5780  RETURN Sum
5790  FNEND
5800  DEF FNHf(T)
5810  Hf=T*(4.203849-T*(5.88132E-4-T*4.55160317E-6))
5820  RETURN Hf*1000
5830  FNEND
5840  DEF FNGrad(T)
5850  Grad=37.9853+.104388*T
5860  RETURN Grad
5870  FNEND
5880  DEF FNTvsp(P)
5890  Tu=110
5900  Tl=10
5910  Ta=(Tu+Tl)*.5
5920  Pc=FNPvst(Ta)
5930  IF ABS((P-Pc)/P)>.001 THEN
5940  IF Pc<P THEN Tl=Ta
5950  IF Pc>P THEN Tu=Ta
5960  GOTO 5910
5970  END IF
5980  RETURN Ta
5990  FNEND
6000  DEF FNPvsv(V)
6010  P=8133.5133+2.236051E+4*V
6020  RETURN P
6030  FNEND
```

PROGRAM TCAL

```
100 ! FILE NAME: TCAL
110 ! REVISED:   December 11, 1983
120 !
130   COM /Cc/ C(7)
140   DIM Emf(10).T(10).D(10)
150   DATA 0.10086091.25727.94369.-767345.8295.78025595.81
160   DATA -9247486589,6.97688E11.-2.66192E13.3.94078E14
170   READ C(*)
180   CLEAR 709
190   BEEP
200   INPUT "ENTER MONTH, DATE AND TIME (MM:DD:HH:MM:SS)".B$
210   J=0
220   OUTPUT 709:"TD":B$
230   OUTPUT 709:"TD"
240   ENTER 709:A$
250   PRINT USING "10X.""Month. date and time  = "".14A";A$
260   BEEP
270   INPUT "ENTER INPUT MODE (1=3054A. 2=FILE)".Im
280   IF Im=1 THEN
290   BEEP
300   INPUT "GIVE A NAME FOR DATA FILE".D_file$
310   CREATE BDAT D_file$.5
320   ELSE
330   BEEP
340   INPUT "GIVE NAME OF EXISTING FILE".D_file$
350   BEEP
360   INPUT "ENTER NUMBER OF DATA RUNS STORED",Nrun
370   END IF
380   BEEP
390   INPUT "GIVE A NAME FOR PLOT FILE".P_file$
400   CREATE BDAT P_file$.5
410   ASSIGN @Plot TO P_file$
420   ASSIGN @File TO D_file$
430   IF Im=1 THEN
440   BEEP
450   INPUT "ENTER BATH TEMPERATURE".T_bath
460   OUTPUT 709;"AR AF20 AL30"
470   FOR I=0 TO 10
480   OUTPUT 709:"AS SA"
490   ENTER 709:Emf(I)
500   NEXT I
510   OUTPUT 713:"T1R2E"
520   WAIT 2
530   ENTER 713:T1
540   OUTPUT 713:"T2R2E"
550   WAIT 2
560   ENTER 713;T2
570   OUTPUT @File:T_bath.Emf(*).T1.T2
580   ELSE
590   ENTER @File:T_bath.Emf(*).T1.T2
600   END IF
610   J=J+1
620   Dwa=0
630   FOR I=0 TO 10
640   T(I)=FNTvsv(ABS(Emf(I)))
650   D(I)=T_bath-T(I)
660   IF I>4 THEN Dwa=Dwa+D(I)
670   NEXT I
680   Dwa=Dwa/6
```

```
690    Dsa=(D(0)+D(1))*.5
700    OUTPUT @Plot;T_bath,Dsa,Dwa
710    PRINT
720    PRINT USING "10X,""Data set number = "",DD";J
730    PRINT USING "10X,""Bath T (C)     QCT-1 (C)     QCT-2 (C)"""
740    PRINT USING "10X,3(3D.3D,7X)";T_bath,T1,T2
750    PRINT USING "10X,""Thermocouple readings (Deg C):"""
760    PRINT USING "10X,6(3D.DD,3X),16X";T(*)
770    PRINT USING "10X,""Discrepancies (Deg C):"""
780    PRINT USING "11X,6(MZ.DD,4X),15X";D(*)
790    BEEP
800    IF Im=1 THEN
810    INPUT "ARE YOU TAKING MORE DATA (1=Y,0=N)?",Go_on
820    IF Go_on=1 THEN 430
830    ELSE
840    IF J<Nrun THEN 430
850    END IF
860    PRINT
870    IF Im=1 THEN
880    PRINT USING "10X,""NOTE: "",DD,"" data sets are stored in file "",14A";J,D
_file$
890    ELSE
900    PRINT USING "10X,""NOTE: Above analysis was performed from file "",14A";D_
file$
910    END IF
920    PRINT USING "16X,""Plot data are stored in file "",10A";P_file$
930    ASSIGN @File TO *
940    ASSIGN @Plot TO *
950    END
960    DEF FNTvsv(Emf)
970    COM /Cc/ C(7)
980    Sum=C(0)
990    FOR I=1 TO 7
1000   Sum=Sum+C(I)*Emf^I
1010   NEXT I
1020   RETURN Sum
1030   FNEND
```

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